THE THIRD

COMPOSITES DURABILITY WORKSHOP

CDW 2000

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August 22-23, 2000

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Kanazawa Institute of Technology

Tokyo, Japan

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13 SUPPLEMENTARY NOTES

14. ABSTRACT

Presentations at the Workshop Included:
Session A: "Design and Testing of Interlocked Grid Panels", and "Fatigue Life Prediction of CFRP/GFRP Bolted Joint Systems" **Session B**: "Thermo-Mechanical Response of Composites at Cryogenic", "Durability Assessment of Polymer Matrix Composite Materials for Use on the Next-Generation SST at National Aerospace Laboratory", and "Status of Project on Advanced Composite Materials for Transportation in Japan" **Session C**: "Recent Advances in Pitch-based Carbon Fibers and Their Composites", Advanced Composite Materials for Satellite Structures in MELCO", and "Spacecraft Structures in the Early 21st Century" **Session D:** "On the Tensile Strength of Carbon Fiber-Unsaturated Polyester Strand Specimens", Modeling Post-Buckled Delaminations in Composites", and "Characterization of Damage Progression in Multidirectional Symmetric FRP Laminates" **Session E:** "An Information System for Composites Durability", "Development of Truss System and Monocoque Panel with CFRP for Long-Span Structures", and "The Application of Fiber Reinforced Plastics in Construction Field of Japan"

15. SUBJECT TERMS

Composite Durability

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a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Thomas D. Kim
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Final Program

THE THIRD COMPOSITES DURABILITY WORKSHOP

CDW 2000

August 22-23, 2000

Tokyo Office, Kanazawa Institute of Technology
Tokyo, Japan

Scope:

Composite materials and structures have served many industries well over the last 25 years. Light weight, corrosion resistance and flexible manufacturing processes have been well established. Cost of fibers has dropped. Design tools are emerging rapidly. In applications in sporting goods and satellites composites have assumed dominant positions.

Durability over the anticipated life of composite materials and structures is a critical issue that brings uncertainties and may be a deterrent for the future of composite materials. Having organic materials as matrices their intrinsic time and temperature dependent properties deserve accurate characterization and rational use in design. The purpose of this workshop is to examine the most advanced methods of determining such properties and seek means for industrial acceptance.

This workshop will bring together people representing the science, engineering and practices needed to bring composites durability in focus. Leaders from government, industry and universities will present their views and recommendations in an informal, intimate atmosphere.

Encouragement and support of this workshop have come from the US National Science Foundation, US Air Force Office of Scientific Research, industrial concerns and Kanazawa Institute of Technology. The co-chairs are Prof. Stephen W. Tsai of Stanford University and Prof. Yasushi Miyano of Kanazawa Institute of Technology.

Technical and Social Program

August 22, Tuesday at International House of Japan

Welcoming Reception	19:00 ~ 21:00

August 23, Wednesday at Tokyo Office, Kanazawa Institute of Technology

Opening Ceremony	9:00 ~ 9:15
Technical Program	9:15 ~ 10:05
Coffee Break	10:05 ~ 10:35
Technical Program	10:35 ~ 11:50
Lunch	11:50 ~12:50
Technical Program	12:50 ~14:05
Coffee Break	14:05 ~14:35
Technical Program	14:35 ~15:50
Coffee Break	15:50 ~16:20
Technical Program	16:20 ~17:35
Closing Ceremony	17:35 ~17:45
Workshop Banquet	18:00 ~20:00

The invited speakers will present all papers in the technical programs.

Presentations by Invited Speakers

August23, Wednesday

Session A (9:15 ~ 10:05) Chair: Isao Kimpara

1. "Design and Testing of Interlocked Grid Panels"
   Stephen W. Tsai, Dongyup Han, Julie Q. Wang and Akira Kuraishi, Stanford University

2. "Fatigue Life Prediction of CFRP/GFRP Bolted Joint Systems"
   Yasushi Miyano, Masayuki Nakada and Naoyuki Sekine, Kanazawa Institute of Technology

Session B (10:35 ~ 11:50) Chair: Stephen W. Tsai

3. "Thermo-Mechanical Response of Composites at Cryogenic"
   Ran Y. Kim, University of Dayton Research Institute

4. "Durability Assessment of Polymer Matrix Composite Materials for Use on the Next-Generation SST at National Aerospace Laboratory"
   Tosiyuki Shimokawa and Hisaya Katoh, National Aerospace Laboratory

5. "Status of Project on Advanced Composite Materials for Transportation in Japan"
   Yasuhiro Yamaguchi, Akira Sakamoto and Minoru Noda, R&D Institute of Metal and Composites for Future Industries

Session C (12:50 ~ 14:05) Chair: Ran Y. Kim

6. "Recent Advances in Pitch-based Carbon Fibers and Their Composites"
   Yoshio Sohda and Tetsuji Watanabe, Nippon Mitsubishi Oil Corporation

7. "Advanced Composite Materials for Satellite Structures in MELCO"
   Tuyoshi Ozaki, Mitsubishi Electric Corporation

8. "Spacecraft Structures in the Early 21st Century"
   Steven Huybrechts and Troy Meink, Air Force Research Laboratory

Session D (14:35 ~ 15:50)   Chair: Yasushi Miyano

9. "On the Tensile Strength of Carbon Fiber-Unsaturated Polyester Strand Specimens"
   Jyunichi Matsui, Venturelabo Co. Ltd. and Zenichiro Maekawa, Kyoto Institute of Technology

10. "Modeling Post-Buckled Delaminations in Composites"
    Tong Earn Tay, National University of Singapore

11. "Characterization of Damage Progression in Multidirectional Symmetric FRP Laminates"
    Isao Kimpara and Kazuro Kageyama, The University of Tokyo

Session E (16:20 ~ 17:35)   Chair: Jyunichi Matsui

12. "An Information System for Composites Durability"
    H. Thomas Hahn, University of California, Los Angeles

13. "Development of Truss System and Monocoque Panel with CFRP for Long-Span Structures "
    Kenichi Sugizaki, Shimizu Corporation

14. "The Application of Fiber Reinforced Plastics (FRP) in the Construction Field of Japan"
    Kozo Kimura and Hiroya Hagio, Obayashi Technical Research Institute

Registration

Workshop registration can be made through the following email address.

miyano@neptune.kanazawa-it.ac.jp (Professor Yasushi Miyano)

Registration fee of 30,000 Yen is payable at registration desk at Tokyo Office of KIT. This fee includes attendance of all technical sessions, a copy of all viewgraphs used by the speakers, lunch, welcoming reception and banquet.

Workshop Location

International House of Japan for Welcoming Reception on August 22, Tuesday
11-16, Roppongi 5-chome, Minatoku, Tokyo 106-0032
Japan
Phone: 81-3-3470-4611
Fax: 81-3-3479-1738

Tokyo Office, Kanazawa Institute of Technology for Technical Program and Banquet on August 23, Wednesday
17-14, Akasaka 2-chome, Minatoku, Tokyo 107-0052
Japan
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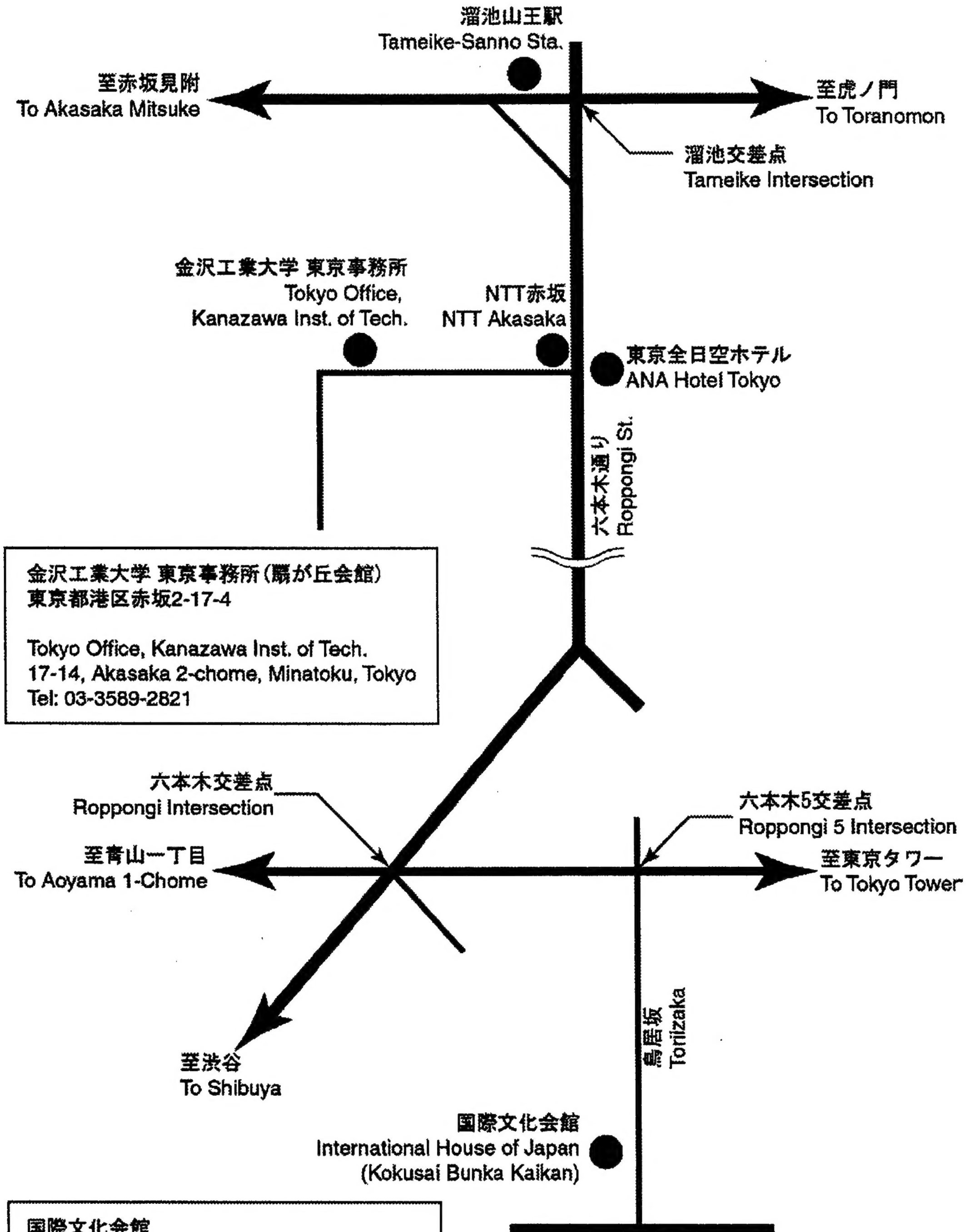

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Design and Testing of Interlocked Grid Panels

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Design and Testing of Interlocked Grid Panels

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Composite grids made from pultruded glass or carbon ribs provide unmatched performance/cost combination of any composite panels. Ribs are unidirectional and have fiber volume fractions of 72 percent for glass and 66 percent for carbon ribs. The respective Young's moduli are 52 and 154 GPa (7.5 and 22 msi.) Grids made from these ribs are competitive in performance with stiffened and sandwich panels.

One of the simplest methods of grid assembly is to cut equally spaced slots into the ribs. Then a square grid is formed by inserting matching slots into on another. Slot cutting can be done on-line, and slotted joint grids can be assembled without fixturing and done on-site.

While slotted joint grids have been used in carpentry for centuries, slots in the ribs reduce the stiffness and strength of the ribs and subsequently those of the grid. Our solution to this problem is to bond rib caps to the grid so the caps can bridge the open slots. The loss of properties of the interlocked grid can then be fully recovered, and more, by the size of the rib caps. Thus ribs contribute directly to the grid properties as if the slots were not there.

These grids are cost effective because ribs are made directly from dry fibers impregnated and cured in a die. The pulling speed is 1 m/min or 1.44 km/day. Multiple ribs can be pulled simultaneously. There is no requirement for tooling, lamination, debalking, bagging, preform, infiltration, autoclaving, clean up, cold storage, and clean rooms. There is practically zero scrap and no consumables.

Grid failure initiates from the root of the slot. The intrinsic weakness of in shear of unidirectional ribs is a limiting design issue. We have tested various configurations of ribs and grids under static and fatigue loading in order to understand the initiation and propagation of the cracks. Understanding of material and processing variables of pultruded ribs can lead to improved grid performance.

Composite grid as a reinforcement of concrete offers many opportunities not readily available for rebar-reinforced concrete. Carbon grids are needed for this application because glass lacks akaline resistance. The mechanism of concrete reinforcement by grids is fundamentally different in that load transfer is done through interlocking rather than friction between rebars and concrete. There is synergy between grid and concrete: grid strengthens concrete and concrete stabilizes grid. Grid can be designed to carry wet concrete leading to self-supporting forms that can be lifted in place and immediately ready for pouring and curing. Speed of contruction and worker's safety can be improved. Carbon grid has a negative thermal expansion. It can lock concrete and eliminate the need for expansion joints. A continuous deck is now feasible. Ubiquitous cracks and potholes in concrete can be things of the past. Soaring structures dreamed by architects can now be designed and built.

Large and small grids made from glass and carbon ribs will be presented. Their load-carrying capabilities with and without concrete will be shown. The toughness of the grid is of particular importance for civil and aerospace applications. One project under consideration is to build grid panels of 4 m x 16 m for a military application. Another project is a wharf that is 100 m long. Field assembly is planned for both projects. Grids must pass the test of mass production and sizes 10 m or larger.

Automation is undoubtedly critical. Pultrusion and slot cutting are already automated. Assembly of slotted joint grid can be done semi-automatically. The most challenging task is the bonding of the rib caps. We have learned from auto industry to use its bonding process. There is a dispenser for adhesive and an x-y robotic frame for laying down the adhesive bead. The curing can then be in seconds. Thus the cycle time of our grids can be very low, in minutes if not seconds.

We are therefore very confident that the interlocked grid will in time find many applications.

Design and Testing of Interlocked Grid Panels

Stephen W. Tsai

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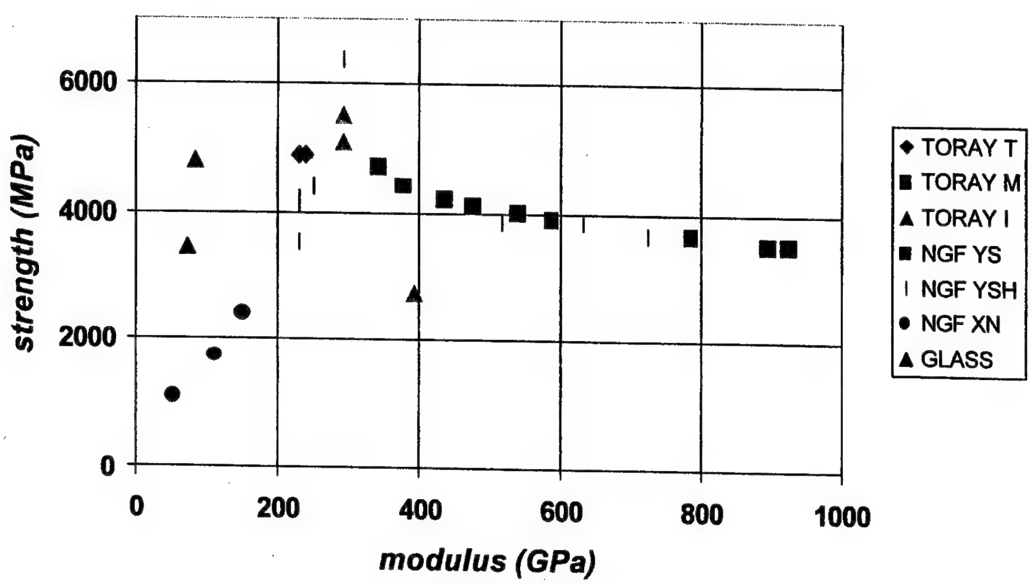
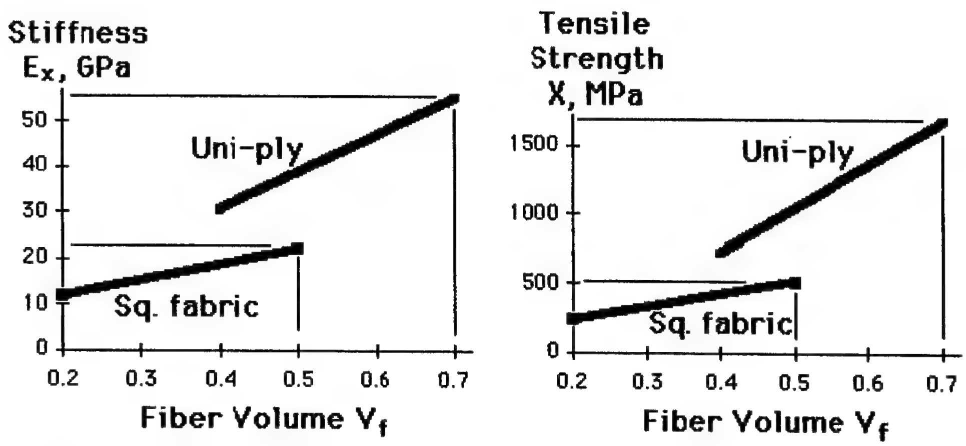
Superior Fiber Properties



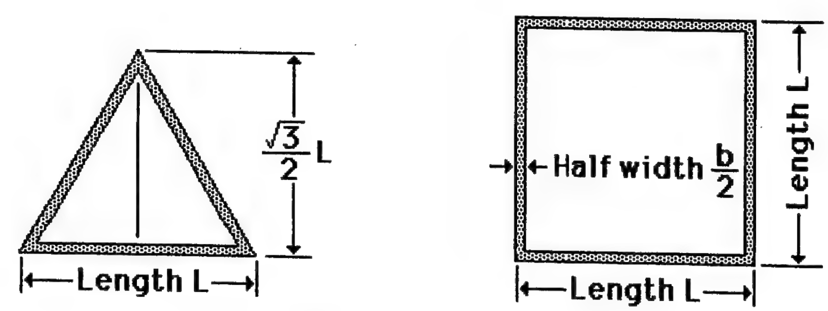
Fiber properties of Toray and Nippon Graphite Fiber

Unidirectional Composite vs. Laminates and Fabrics



Superior uni-ply glass composites over other fiber architecture
Data from Vetrotex

Stiffness of Grids



$\pi/3$ ISOGRID $\quad f = \frac{2\sqrt{3}}{L/b}$

$E = f/3\ E_{rib}$

$\nu = 1/3$

$G = 3/8\ E = f/8\ E_x$

SQUARE GRID $\quad f = \frac{2}{L/b}$

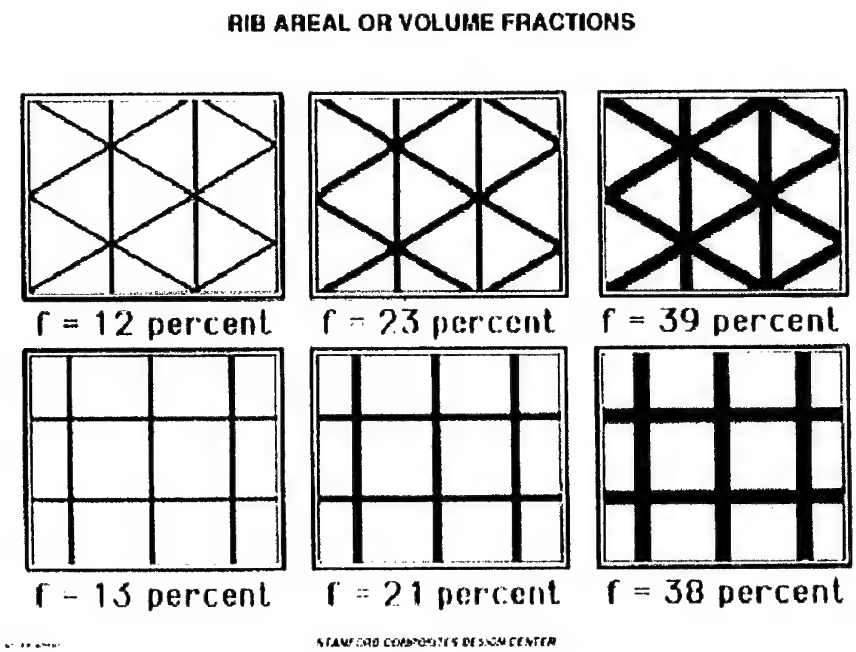
$E_x = E_y = b/L\ E_{rib} = f/2\ E_{rib}$

$\nu_x = 0$

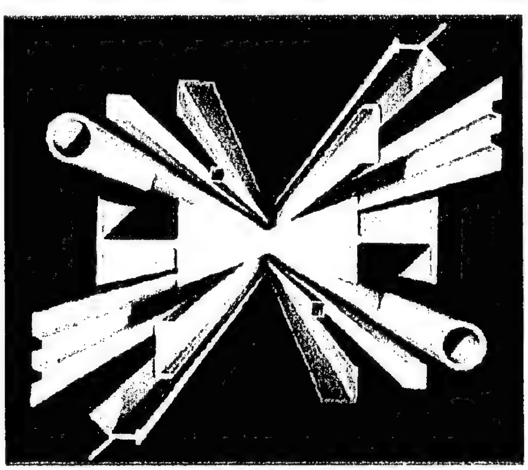
$G_x = 0$

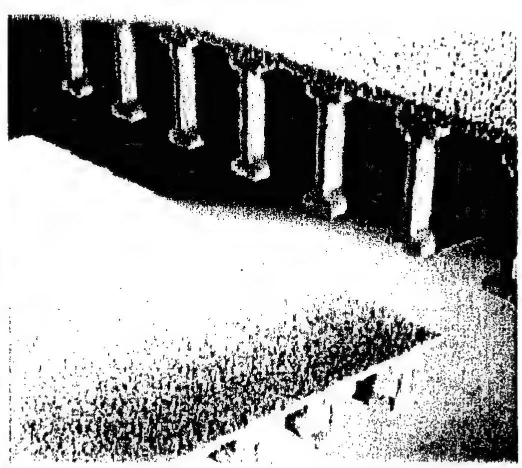
Simple rule-of-mixtures relations for grid and rib stiffness can be found in:
S. Tsai, et al, "Manufacturing and Design of Composite Grids" 3-D Textile Reinforcements in Composite Materials, ed A. Miravete, CRC Press (1999), pp 151-179.

Rib Fraction



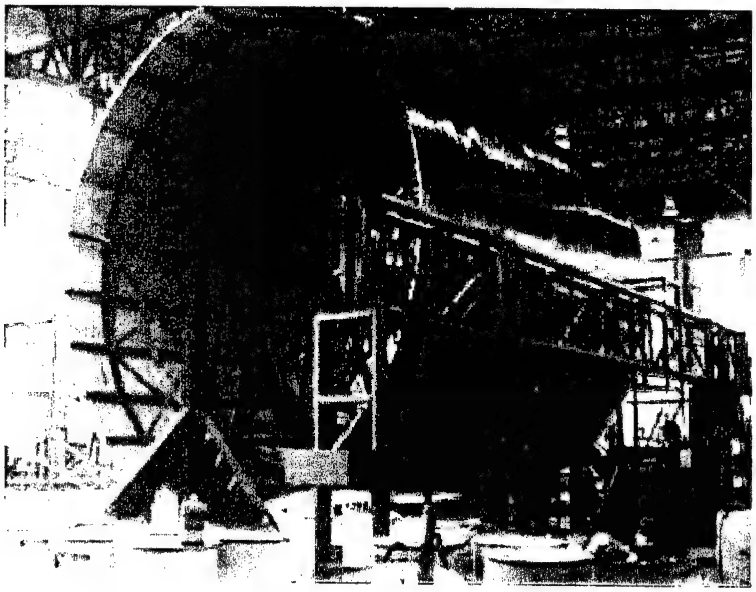
Pultrusion





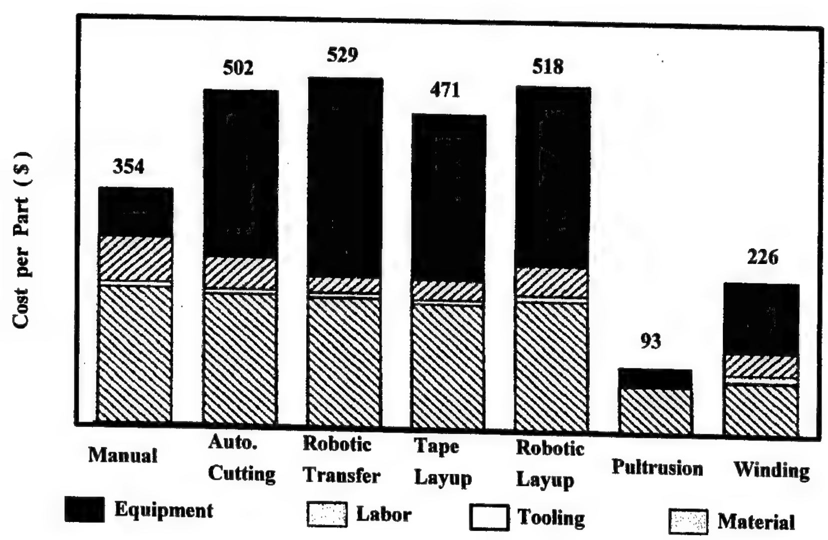
One of the most cost-effective and reliable processes for composite structural members. Composite grids can take full advantage of this pultrusion process.

Filament Winding



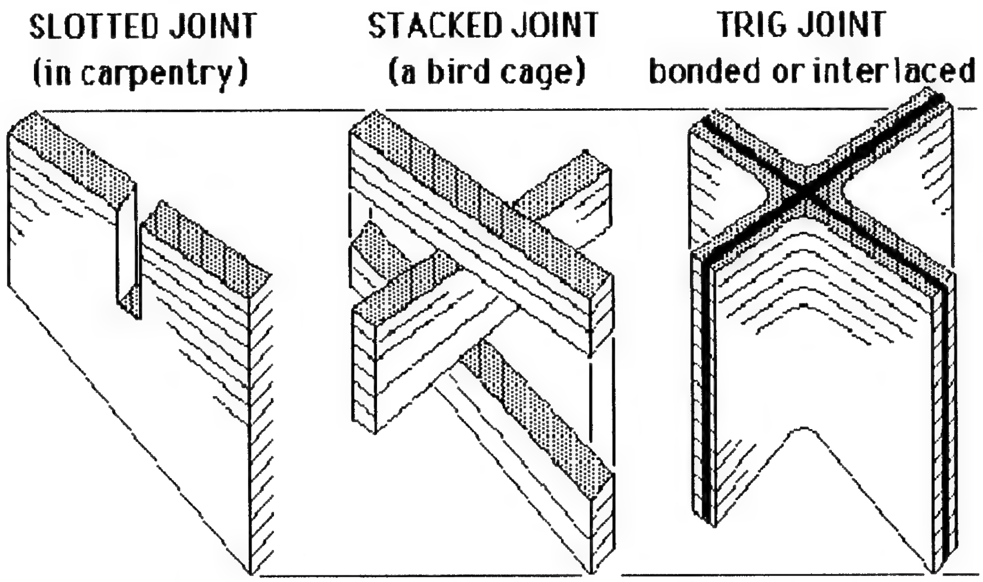
Filament winding of a 20 foot diameter by Dura-Wound. Even larger tanks have been wound in horizontal or vertical position.

Low Cost



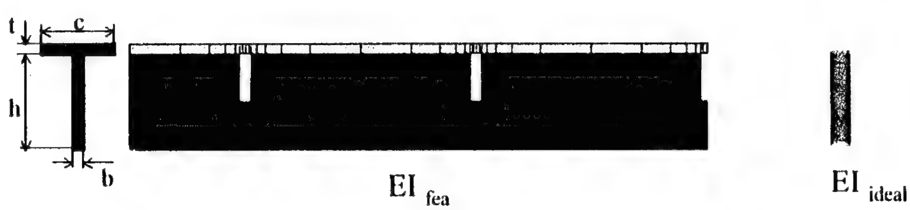
* Timothy G. Gutowski, "Cost, automation, and design", ***Advanced Composites Manufacturing***, p. 525, Wiley Inter-Science, 1997

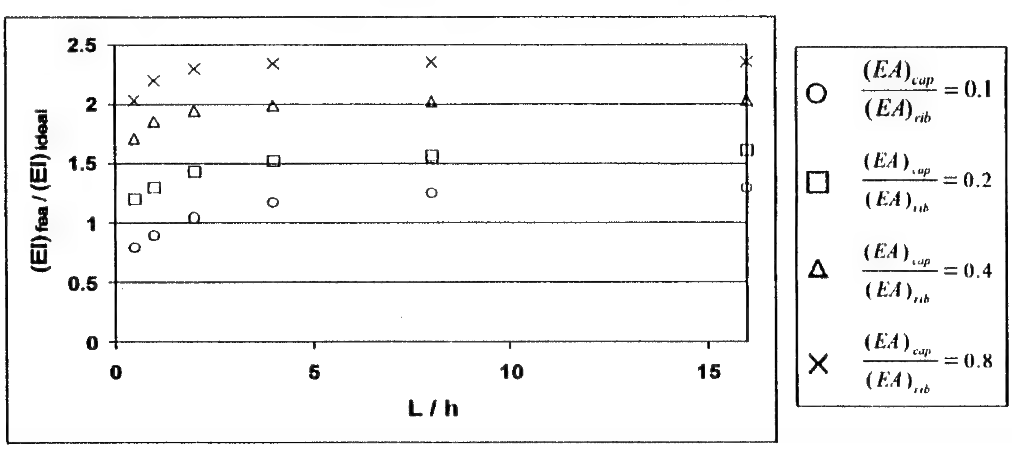
Grid Joints



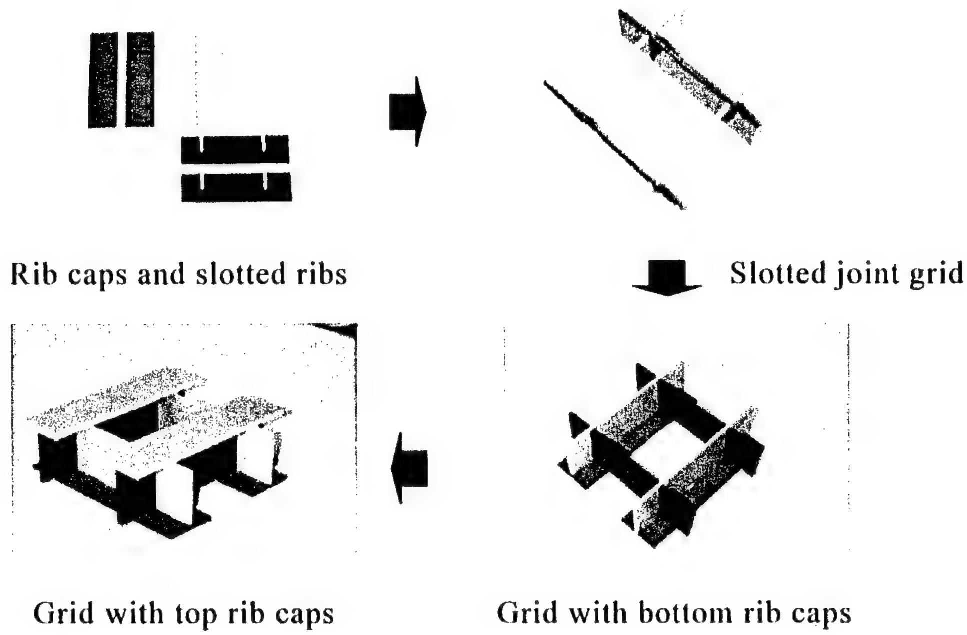
Joints can be the weak link of a grid. They are the most challenging tasks in design and manufacturing.

Cap Reinforced Slotted Rib

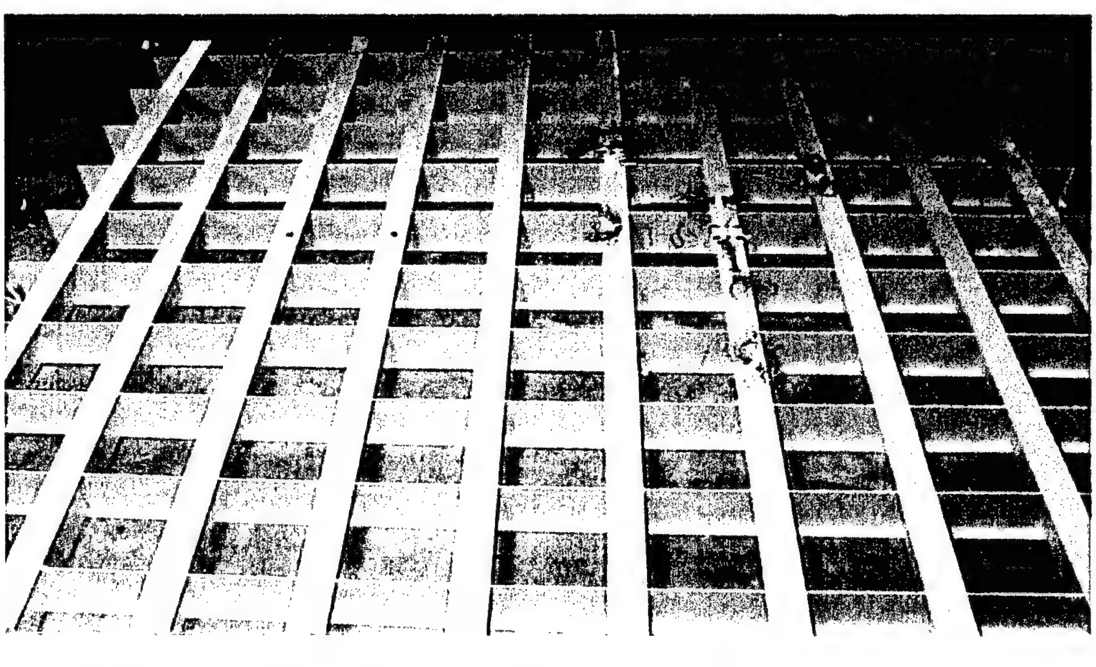




Interlocked Composite Grids

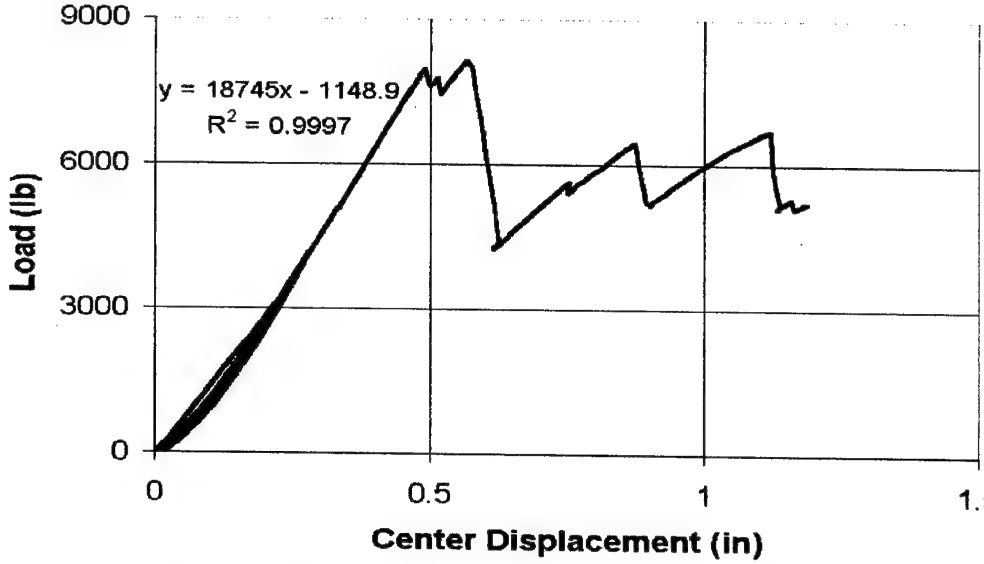


Completed Grid (10’ x 10’ x 6”)



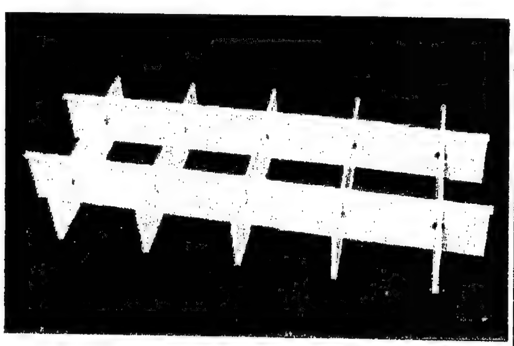
Field assembly of large grid is feasible and cost-effective.

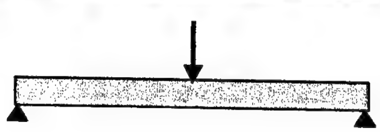
Static Test

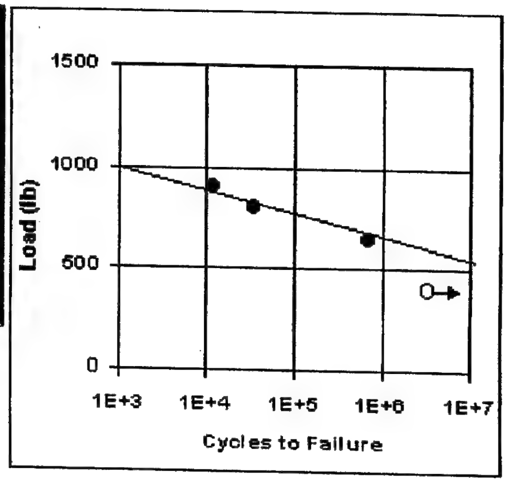


Four edges simply support and a concentrated load at center. Loading and unloading shows no permanent deformation before ultimate load. Multiple, progressive failures after the ultimate.

Fatigue Test

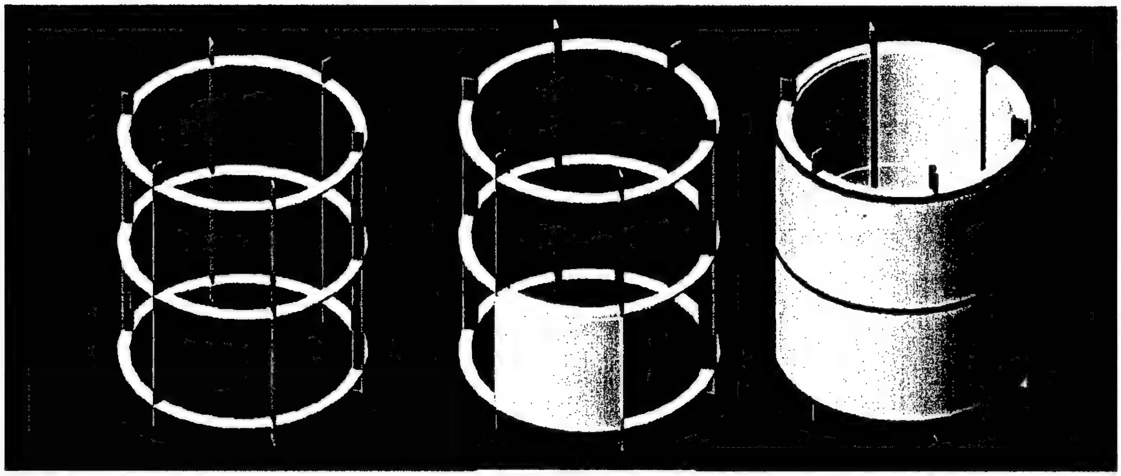






A specimen for fatigue and static tests. Most failures initiated at the root of slots. Crack growth, however, is stable. Fatigue strength of the grid is outstanding.

Interlocked Composite Grid Cylinder

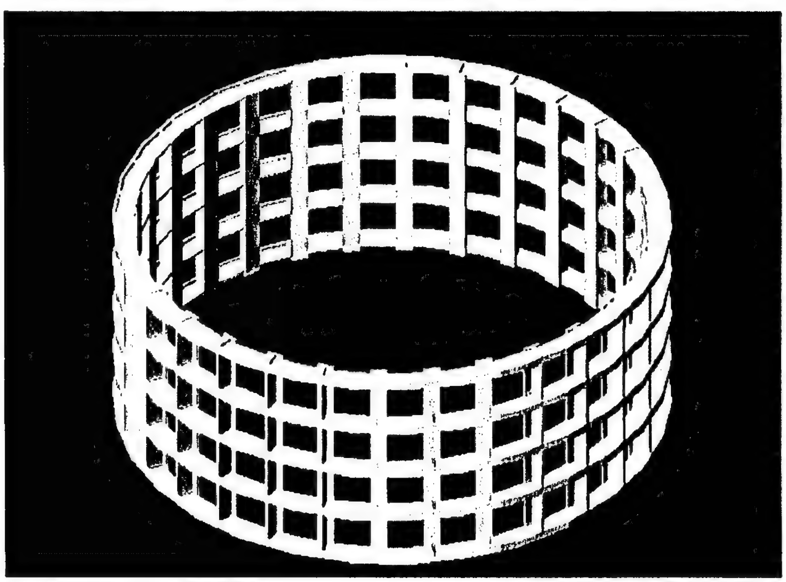


•Slotted joint ribs are assembled.

•Inner caps are bonded and blocks are inserted.

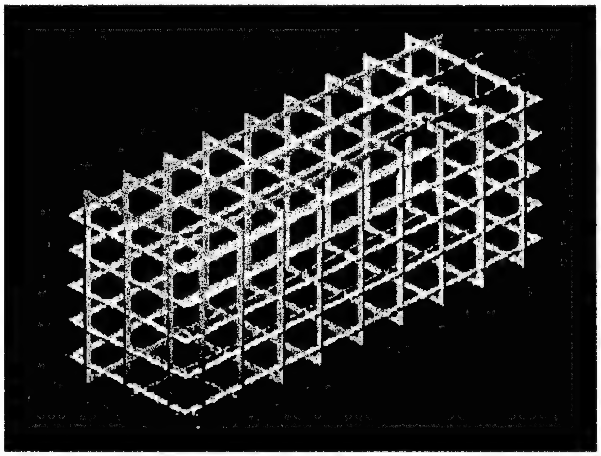
•Complete cylinder with block inserts and rib caps.

Interstage Adapter

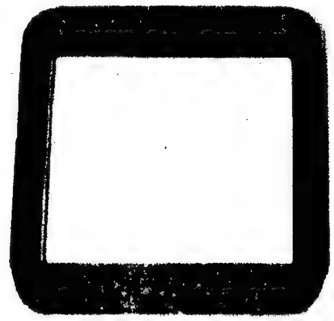


Diameter = 61 inches, Height = 24 inches

An Interlocked Rectangular Grid

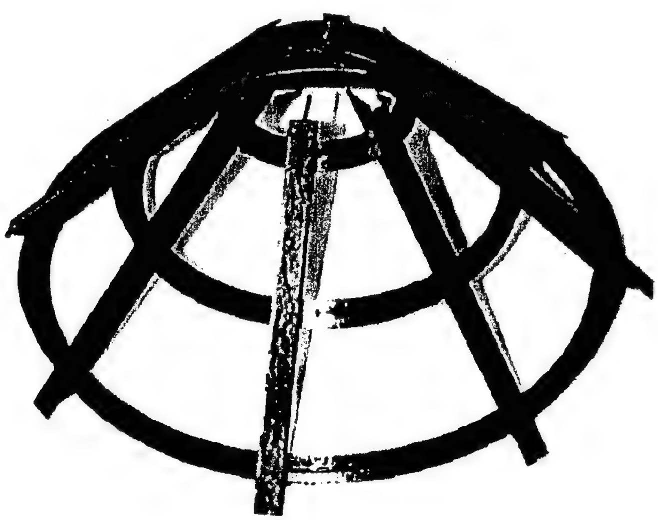


An interlocked rectangular cage



A filament wound loop

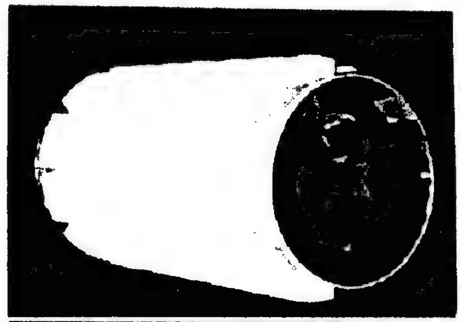
Interlocked Composite Grid Cone



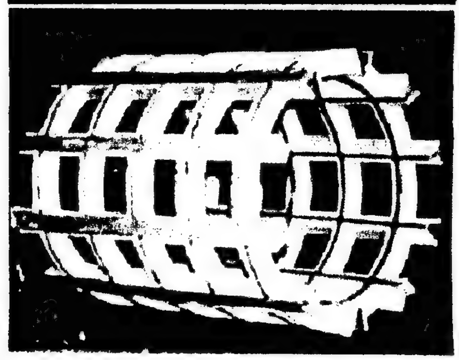
Foam or ceramic inserts can be placed in cell openings to stabilize the ribs, and to provide shear stiffness and to complete closure for flat, cylindrical and conical shells.

[0/90] Interlaced Gird

Square tools positioned onto a mandrel to provide grooves for [0/90] interlace



Interlace placed in grooves by wet filament winding



[±45] Interlaced Grid

Tooling rotate 45 degree to form a helical grid.

Top is glass composites grid with tooling shown in yellow. Bottom is same interlaced grid using carbon composites.

Unmatched Opportunities

Composite grids offer revolutionary opportunities:

High structural performance derived from uni-plies

Low cost pultrusion and filament winding available

Flexible assembly eliminates size limitation

Inserts into open cells can be multi-functional

Modular design offers easy inspection and repair

Challenges

Composite grids must overcome many challenges:

Carbon pultrusion is still in research

Low shear and transverse tensile strengths of uni-ply is intrinsic

Inefficiency of rib intersections or joints

Confidence in bonded structure (rib caps)

Quality production in a rugged environment

Conclusions

Composite grids offer revolutionary opportunities.

Prior examples: Wellington, A-340, Russian missiles

Low risk: use current, though not optimized, materials

Short time: prototype can be built and tested in one year

Payoff is phenomenal: a new way of thinking composites

Large volume applications can finally be here!

Interlocked Grid Airframe

Stephen W. Tsai
Akira Kuraishi

Department of Aeronautics and Astronautics
Stanford University

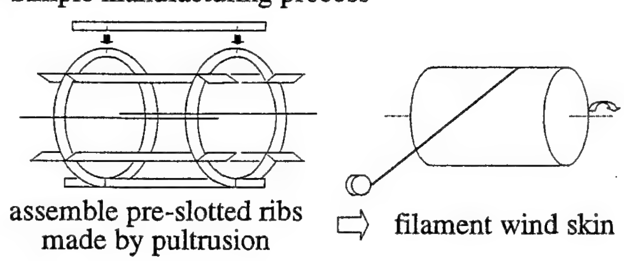
June 28, 2000

Grid Airframe

(1) **High performance**
- Efficient unidirectional composites

(2) **Low cost**
- Cost effective **pultrusion** and **filament winding**

(3) **Easy to manufacture**
- Simple manufacturing process



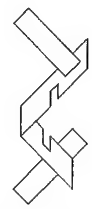
Interlocked Grid

*Slots and **caps** improve the grid performance*

Precut Slots

(1) Provide **accurate assembly**

(2) Create **stress concentration**

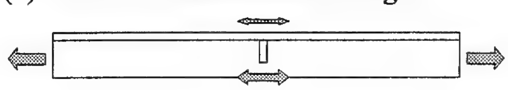


Interlocking

Bonded Caps

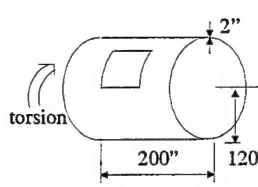
(1) Provide **load path**

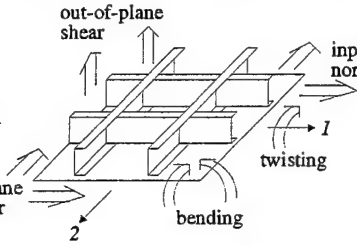
(2) **Recover stiffness and strength**



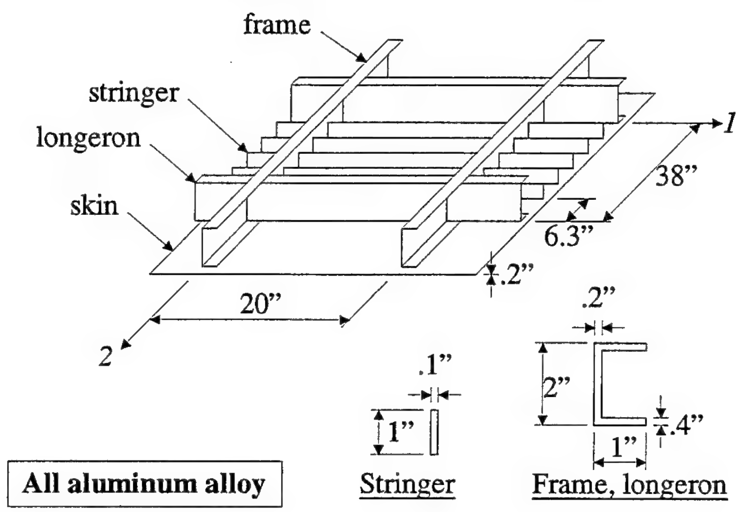
Airframe Comparison

type of airframe		conventional airframe	aluminum sandwich	grid airframe w/ inserts	grid airframe w/ stiffeners
total weight	(lb)	4600	3200	3100	2000
specific stiffness	inplane normal	1	1.1	1.5	2.3
	inplane shear	1	1.1	0.9	1.3
	bending	1	1.0	3.5	5.6
	twisting	1	0.7	0.9	1.3
	out-of-plane shear	1	0.9	2.6	1.8
specific strength	axial compression	1	N/A	N/A	0.9
	axial tension	1	1.2	1.0	1.3
	torsion	1	1.1	N/A	0.5

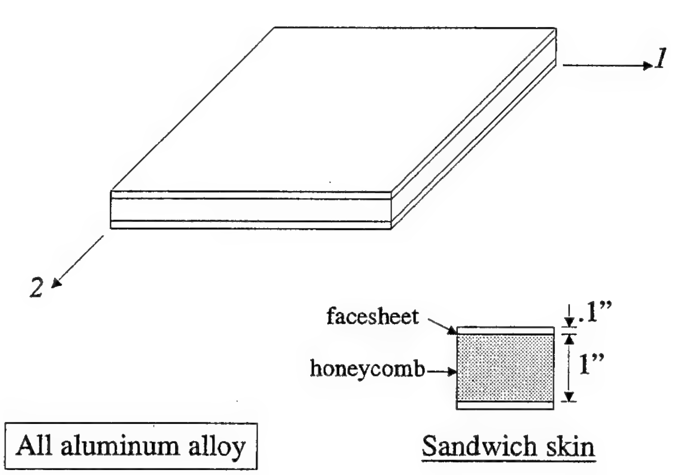




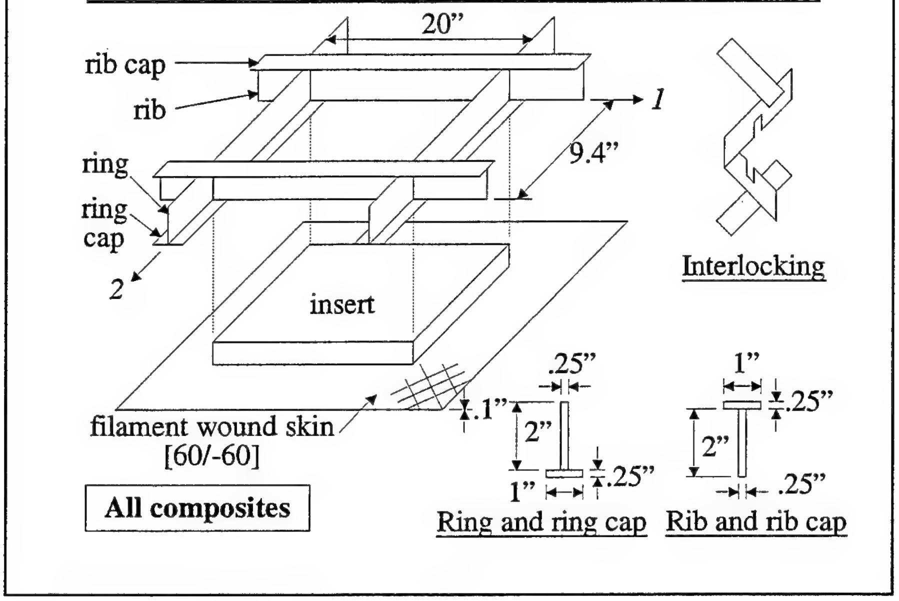
Conventional Airframe (baseline)



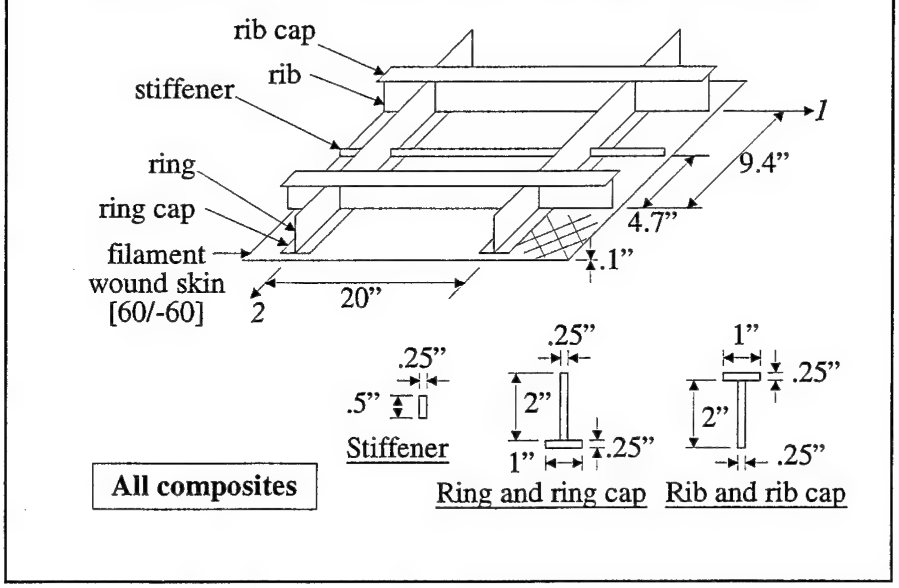
Sandwich Airframe



Grid Airframe with Inserts



Grid Airframe with Stiffeners

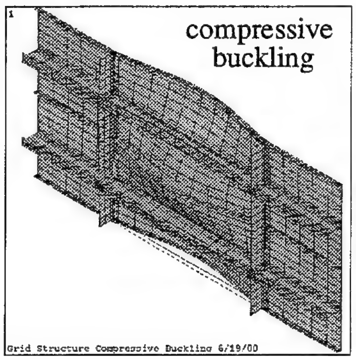


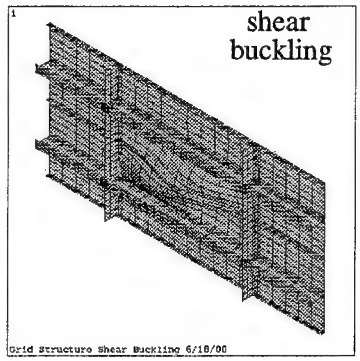
Strength Analysis

Strength of the grid airframe is controlled by

(1) **Buckling** of the thin skin (shown below)

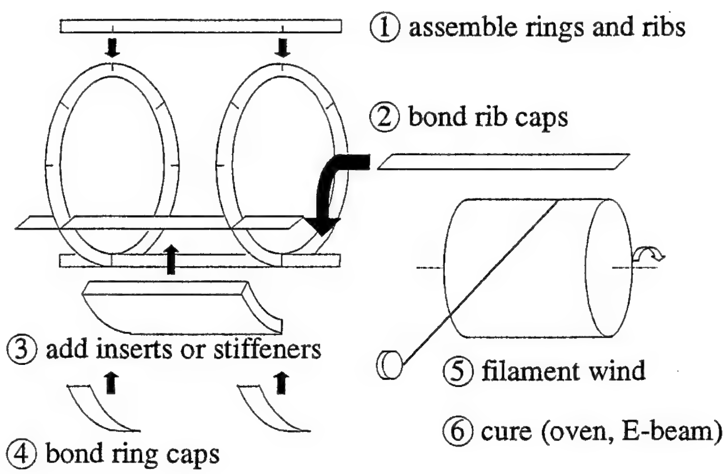
(2) **Stress concentration** at the slots





Grid Airframe Assembly

***Simple** and **low cost** manufacturing process*

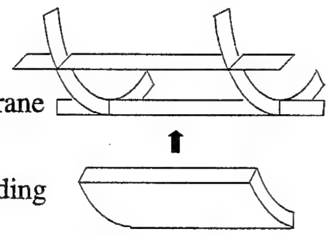


Inserts

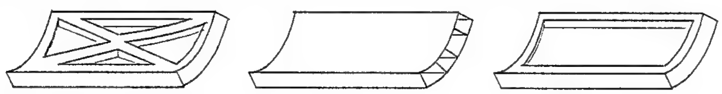
*Inserts add **flexibility** to the design*

Inserts can provide

(1) Shear rigidity
(2) Internal/external pressure membrane
(3) Acoustic/thermal insulation
(4) Smooth surface for filament winding



Modular design enables easy design and manufacturing



Typical Airframe Dimensions

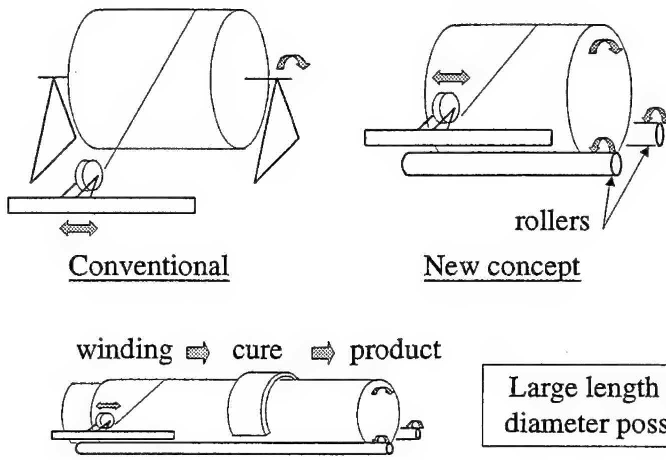
***Grid airframe** can be used for wide selection of dimensions*

	Diameter	Length
>300 passengers		
Boeing 777-200	19ft (5.9m)	209ft (64m)
Boeing 747-400	20ft (6.1m)	232ft (71m)
Airbus 3xx-200	24ft (7.1m)	260ft (78m)
<50 passengers (Regional Jets)		
Bombardier CRJ200	9ft (2.7m)	87ft (27m)
Embraer ERJ145	7ft (2.1m)	98ft (30m)

All examples are semi-monocoque structures made of aluminum alloy.

New Filament Winding Concept

New concept enables winding ***large airframes***



Large length and diameter possible

Conclusion

Interlocked Grid Airframe is

(1) **High performance**

(2) **Low cost**

(3) **Easy to manufacture**

and has potential for wide range of applications

Fatigue Life Prediction of CFRP/GFRP Bolted Joint Systems

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Fatigue Life Prediction of CFRP/GFRP Bolted Joint Systems

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Abstract

Developing a testing procedure to establish the lifetimes of polymer composites and structures in extreme service environments is becoming a high priority. With service lifetimes measured in years, it is almost unthinkable to do real time testing under a variety of conditions. An accelerated testing methodology is vitally needed for polymer composites.

The most important scientific basis to be used in the accelerated testing of polymer composites and structures is the time-temperature superposition principle. In this method, developed mainly for polymeric based materials, elevated temperature states are used to accelerate the mechanisms of mechanical and chemical degradation which occur under loads over very long times. The method has been widely employed to characterize non-destructive properties, and recently it has been shown remarkable success in characterizing failure properties. The degree of acceleration per increment of elevated temperature is found through the use of the time-temperature superposition hypothesis, along with a sophisticated menu of properties testing procedures.

We proposed a prediction method for long-term fatigue strength of polymer composites under an arbitrary stress ratio, frequency and temperature from the data, for various temperatures, of constant strain rate (CSR) tests for several constant strain-rates and of fatigue test at a single frequency based on the above mentioned hypothesis. The method rests on the four hypotheses for polymer composites:

(A) Same failure mechanism for CSR, creep and fatigue failure
(B) Same time-temperature superposition principle for all strengths
(C) The linear cumulative damage law for monotonic loading
(D) Linear dependence of fatigue strength upon stress ratio.

When these hypotheses are met, the fatigue strength under an arbitrary combination of stress ratio, frequency and temperature can be determined based on the following test results: (a) Master curve of CSR strength and (b) Master curve of fatigue strength for zero stress ratio. The master curve of CSR strength is constructed from the test results at several constant strain-rates for various temperatures. On the other hand, the master curve of fatigue strength for zero stress ratio at an arbitrary combination of frequency and temperature can be constructed from tests at a single frequency for various temperatures using the time-temperature superposition principle for CSR strength.

In this paper, the proposed method is introduced and the master curves of fatigue strength of CFRP measured by strand tension, longitudinal bending and transverse bending tests based on the proposed method are shown. The master curves of tensile fatigue load for various GFRP/metal joints are also shown. We can understand clearly by using these master curves that the dependence of the fatigue strength on time, temperature and number of cycles to failure is very different from each other.

Additionally, the range of validity of the proposed method for various FRPs and joint structures is cleared. For CFRP consisting PAN based fiber and epoxy resin, the four hypotheses and thus the proposed method holds for all fiber arrangement and loading directions; uniaxial, longitudinal, transverse and satin-woven. The long-term fatigue strengths for this CFRP can be predicted by using the proposed method. However, some of the hypotheses do not hold for composites with PEEK matrix and for composites with Pitch based carbon fibers and Glass fibers. Therefore, the prediction method is not applicable for these FRPs. Here, PEEK resin is not thermorheologically simple and Pitch based carbon fiber and glass fibers show time dependent failure behavior themselves. We also carried out axial tests for various joints consisted from GFRP and metal. For these joints, the four hypotheses hold. Thus, the prediction

methodology is applicable for these joints.

Furthermore, the characteristics of tensile fatigue behavior for GFRP /metal and CFRP/metal bolted joints are cleared by comparing the master curves of fatigue failure load for these bolted joints.

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Fatigue Life Prediction of CFRP/GFRP Bolted Joint Systems

by

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August 22-23, 2000
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BACKGROUND

The most important scientific basis to be used in the accelerated testing of polymer composites and structures is the time-temperature superposition principle.

In this method, developed mainly for polymeric based materials, elevated temperature states are used to accelerate the mechanisms of mechanical and chemical degradation which occur under loads over very long times.

The method has been widely employed to characterize non-destructive properties, and recently it has been shown remarkable success in characterizing failure properties.

The degree of acceleration per increment of elevated temperature is found through the use of the time-temperature superposition hypothesis, along with a sophisticated menu of properties testing procedures.

OBJECTIVE

A prediction method for long-term fatigue strength of Polymer Composites at an arbitrary stress ratio, frequency, and temperature from limited test data and based on the following hypotheses has been proposed (1997).

(A) Same Failure Mechanism for CSR, Creep, and Fatigue Failure over the same time and temperature

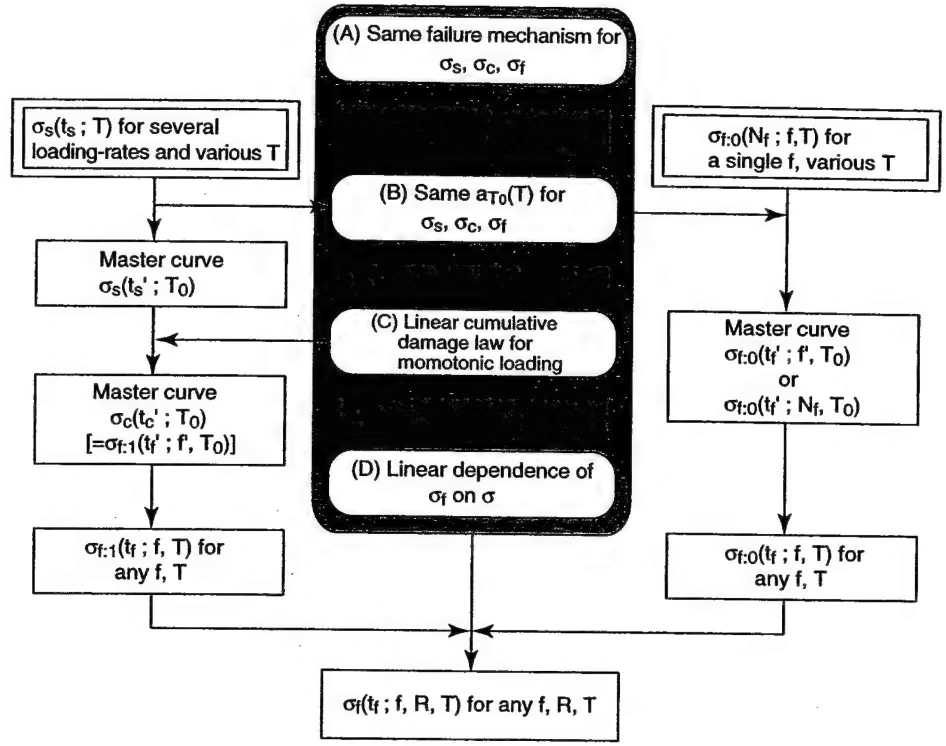
(B) Same Time-Temperature Superposition Principle for all strengths

(C) Linear Cumulative Damage Law for monotonic loading

2-5 (D) Linear Dependence of fatigue strength upon stress ratio

In this paper:

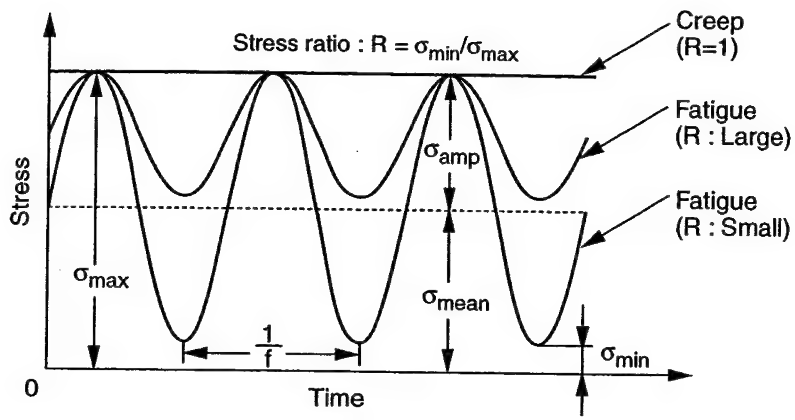
- -Introducing the proposed method
- -Showing the master curves of fatigue strength of various CFRPs and GFRP/metal joints
- -Clearing the range of validity of the proposed method for various FRPs and joint structures
- -Comparing the master curves of fatigue failure load for GFRP/metal and CFRP/metal bolted joints



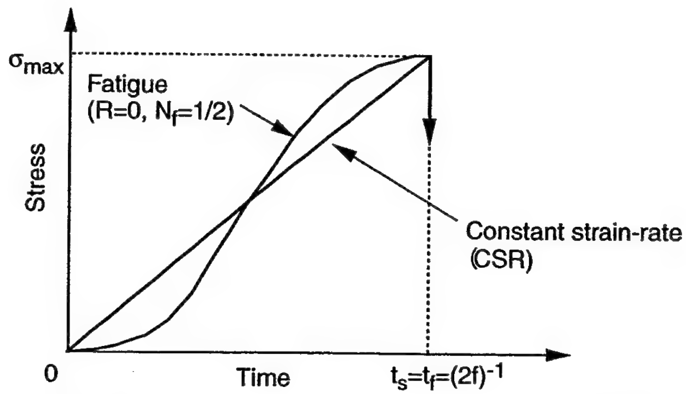
T, T_0	:	temperature, reference temperature
f, f'	:	frequency, reduced frequency
t_s, t_c, t_f	:	time to failure under CSR(Constant Strain Rate), creep and fatigue loadings
t_s', t_c', t_f'	:	reduced time to failure
$a_{T0}(T)$	:	time-temperature shift factor ($a_{T0}(T)=t_s/t_s'=t_c/t'_c=t_f/t_f'=f'/f$)
R	:	stress ratio ($R=\sigma_{min}/\sigma_{max}$)
N_f	:	number of cycles to failure ($N_f=f \cdot t_f$)
σ_s, σ_c, σ_f	:	CSR, creep and fatigue strength
$\sigma_{f:0}$, $\sigma_{f:1}$	:	σ_f for R=0 and R=1

Fig.1 Fatigue Life Prediction Methodology for Polymer Composites

Hypothesis A: Same failure mechanism for CSR, creep, and fatigue failure



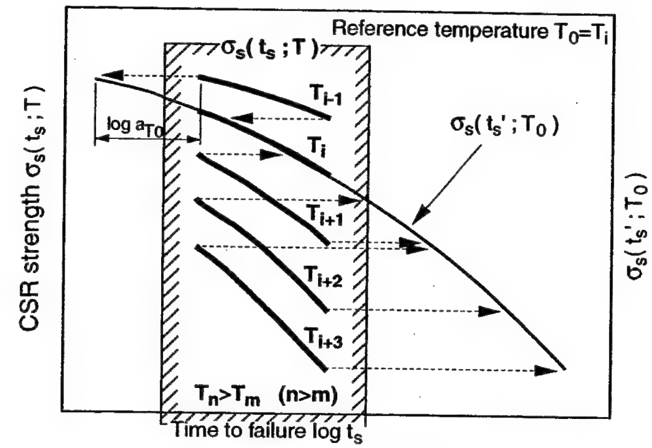
Creep test as fatigue test : R=1, $t_c=t_f$



CSR test as fatigue test : R=0, N_f=1/2, $t_s=t_f=(2f)^{-1}$

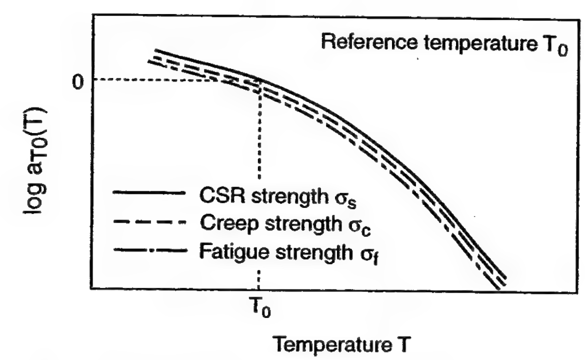
Fig. 2

Hypothesis B: Same time-temperature superposition principle for all strengths



log t_s - log t_s' = log $a_{To}(T)$

where $a_{To}(T)$: Time-temperature shift factor



Time-temperature shift factor $a_{T0}(T)$ versus temperature

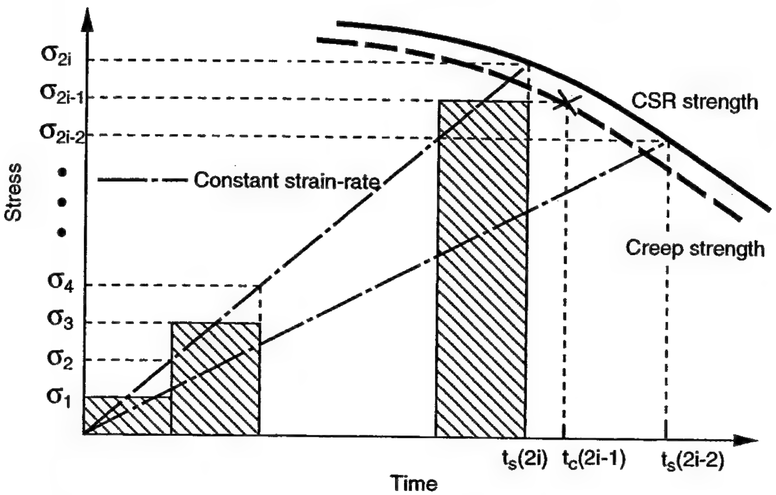
Fig. 3

Hypothesis C: Linear cumulative damage law for monotonic loading

$$\int_0^{t^*} \frac{dt}{t_c[\sigma(t)]} = 1$$

where $t_c(\sigma)$: Creep failure time for stress σ

t^* : Failure time under stress history $\sigma(t)$



Scheme :

σ_i(i = 1, 2, ···) : An equally spaced increasing sequence of stress with σ_0=0

$t_s(i)$, $t_c(i)$: CSR and creep failure time associated with σ_i

Replacing a linear stress history for CSR loading by a staircase function:

$\sigma_s(t) = \sigma_{2p+1}[\ \sigma_{2p} < \sigma_s < \sigma_{2p+2},\ p = 0, 1, 2, \cdots]$

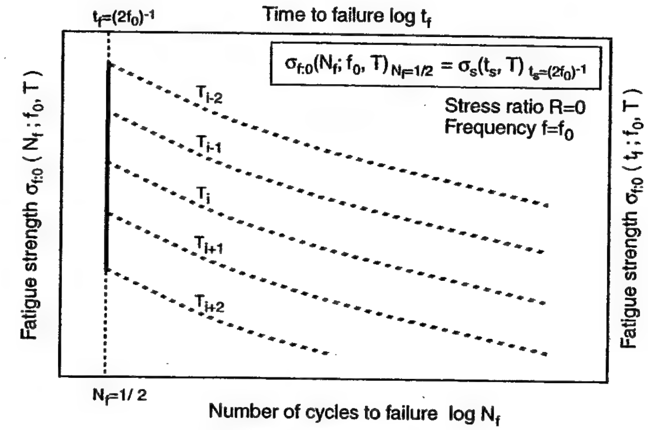
Then the linear cumulative damage law gives the following equations.

$t_c(1) = t_s(1)$

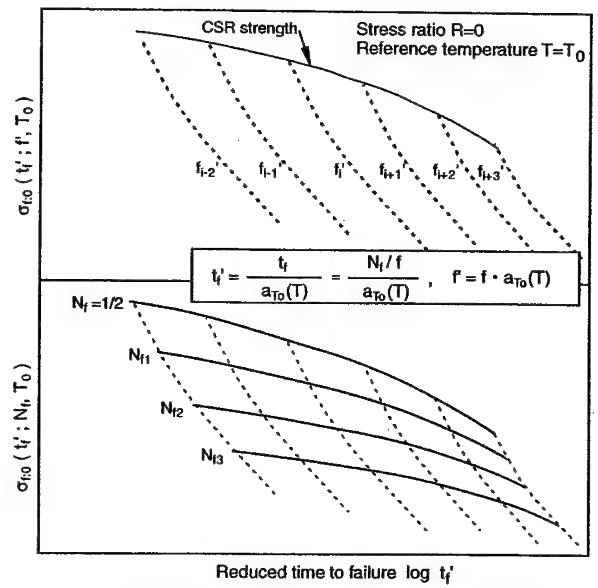
$$t_c(2i-1) = \frac{t_s(2i)\,t_s(2i-2)}{i\,t_s(2i-2) - (i-1)t_s(2i)} \quad (i = 2, 3, 4, \cdots)$$

Fig. 4 Construction of creep strength from CSR strength

Hypothesis A and Hypothesis B



S-N curves



Master curves of fatigue strength

Fig. 5

2-8

Hypothesis D: Linear dependence of fatigue strength upon stress ratio

Information Available at This Stage

(a) The fatigue strength $\sigma_{f:1}(t_f'; T_0)$ for stress ratio R = 1
where t_f' : reduced time to failure at reference temperature T_0

(b) The fatigue strength $\sigma_{f:0}(t_f', N_f, T_0)$ for stress ratio R = 0

Fatigue strength, σ_f (t_f ; R, f, T) at an arbitrary stress ratio R, frequency f, and temperature T

$$\sigma_f(t_f';R,f',T_0) = \sigma_{f:1}(t_f';f',T_0)R + \sigma_{f:0}(t_f';f',T_0)(1 - R)$$

or

$$\sigma_f(t_f;R,f,T) = \sigma_{f:1}(t_f;f,T)R + \sigma_{f:0}(t_f;f,T)(1 - R)$$

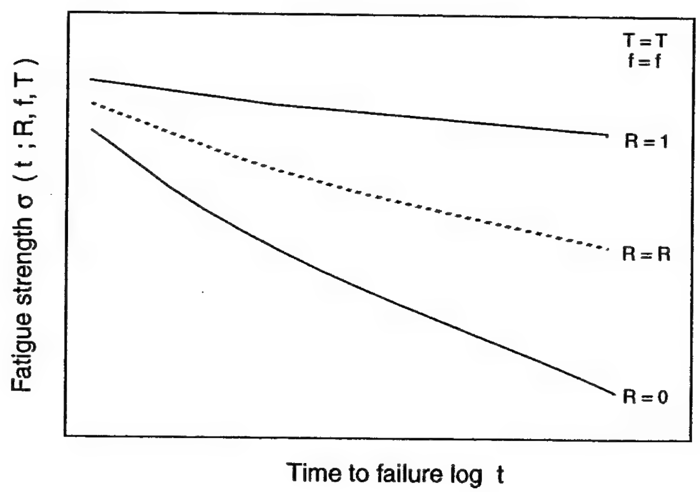


Fig. 6

Estimation of CSR and fatigue tests

Example : Bending tests for CFRP laminates

CSR Test

Loading rate : 5 steps (0.01 ~ 100mm/min)

temperature : 5 steps (RT ~ 120°C)

Number at each step : 3 specimens

Total number of specimens : 75 specimens

Number of weeks : 4 weeks

Fatigue test (R=0.05, Maximum number of cycles : 10^6)

Frequency : 1 step (f=5Hz)

Temperature : 4 steps (RT ~100°C)

Number at each step : 20 specimens

Total number of specimens : 80 specimens

Number of weeks : 12 weeks

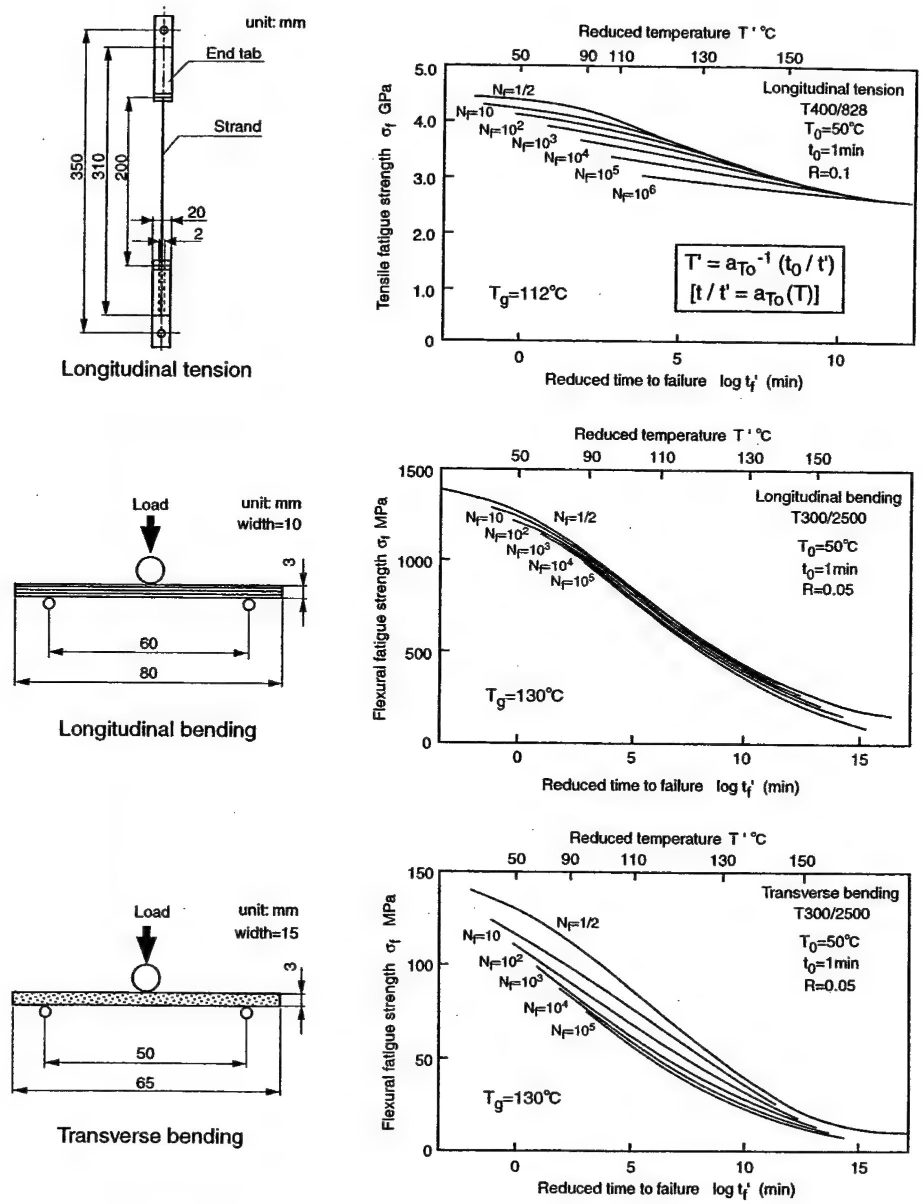


Fig. 7 Master curves of fatigue strength of CFRP

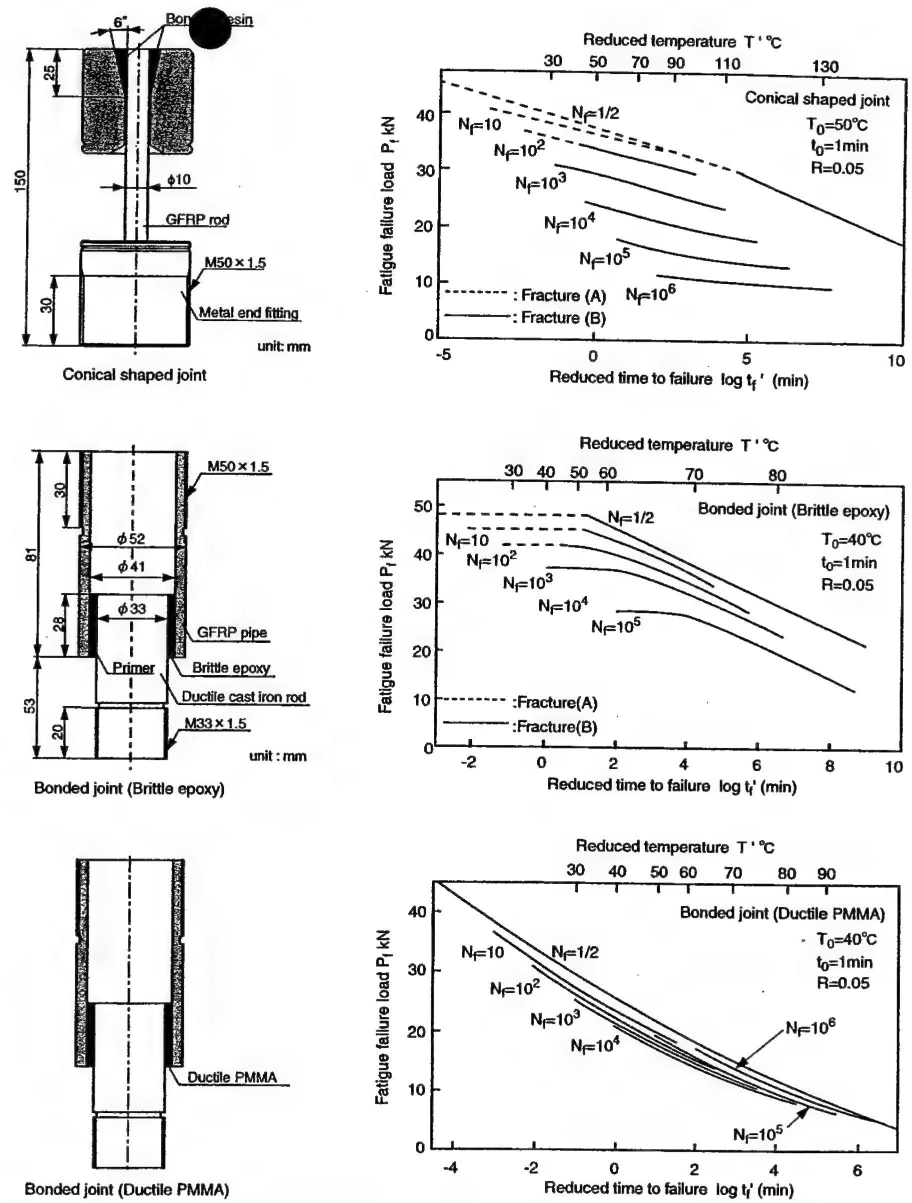


Fig. 8 Master curves of fatigue failure load of various GFRP/metal joints

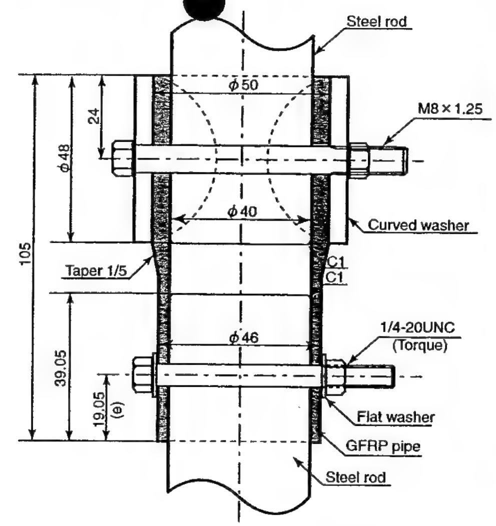
Table 1 Applicability of prediction method to various FRPs and joint structures

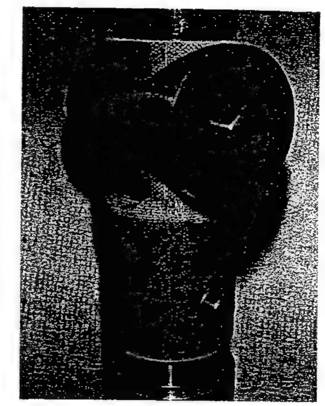
Fiber		Matrix	Type	Fiber/matrix	Loading direction	Hypothesis (A)	(B)	(C)	(D)
Carbon	PAN	Epoxy	UD	T400/828	LT	◎	◎	◎	◎
				T300/2500	LB	◎	◎	◎	◎
					TB	◎	◎	◎	◎
			SW	T400/3601	LB	○	○	○	○
		PEEK	UD	T300/PEEK	LB	○	×	×	△
					TB	△	×	×	×
	Pitch	Epoxy	UD	XN40/25C	LB	○	△	×	○
Glass		Epoxy	SW	E-Glass/Epoxy	LB	○	△	○	×

Notice UD : Unidirectional SW : Stain Woven
LT : Longitudinal Tension LB : Longitudinal Bending
TB : Transverse Bending

FRP Joint System	Hypothesis (A)	(B)	(C)	(D)
Conical Shaped Joint of GFRP/Metal	◎	◎	◎	◎
Brittle Adhesive Joint of GFRP/Metal	◎	◎	◎	◎
Ductile Adhesive Joint of GFRP/Metal	◎	◎	◎	◎
Bolted Joint of GFRP/Metal	○	○	○	○
Bolted Joint of CFRP/Metal	-	-	-	-

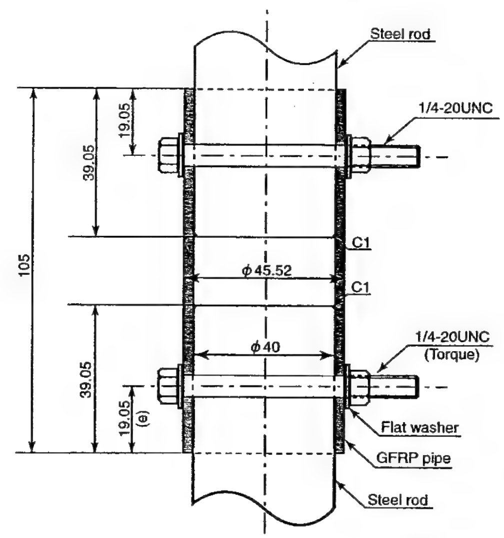
Hypotheses
(A) Same failure mechanism for CSR, creep, and fatigue failures
(B) Same time-temperature superposition principle for all failure strengths
(C) Linear cumulative damage law for monotonic loading
(D) Linear dependence of fatigue strength upon stress ratio

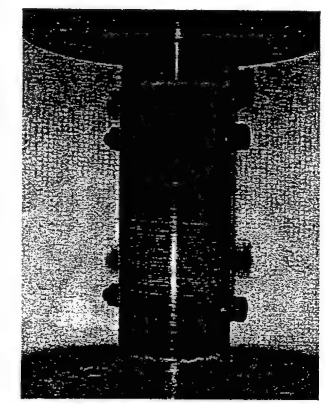




GFRP pipe: Glass fibers/epoxy resin [Plain woven cloth]

GFRP/metal bolted joint system





CFRP pipe: Carbon fibers/epoxy resin $[0/45/90/-45]_3$

CFRP/metal bolted joint system

Fig. 9 GFRP/metal and CFRP/metal bolted joint systems

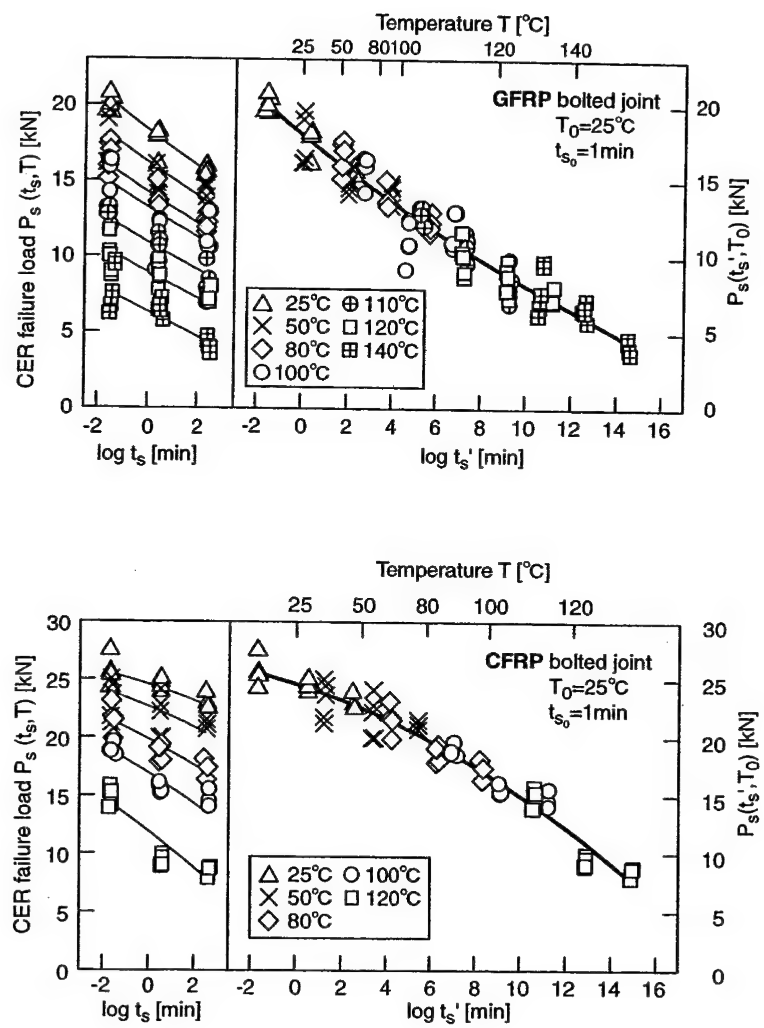


Fig. 10 Master curves of CER failure load

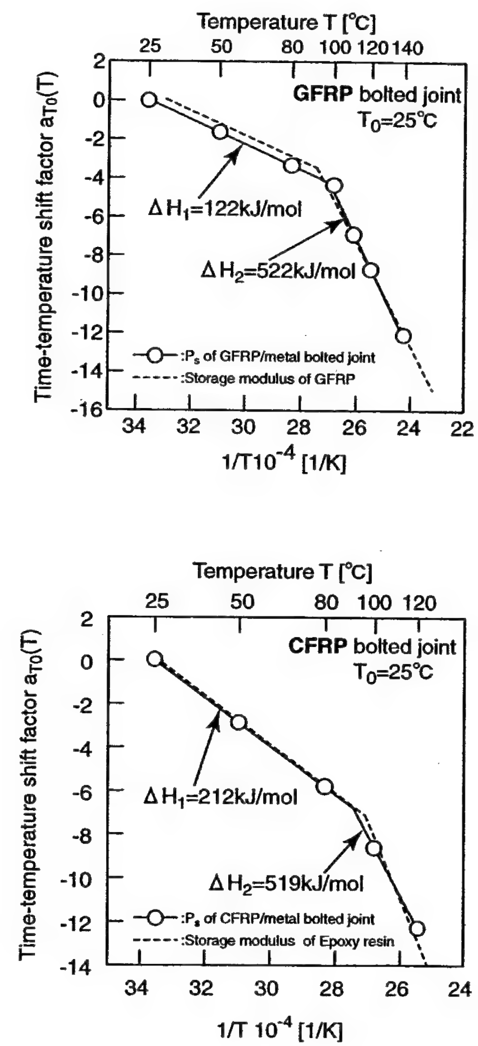


Fig. 11 Time-temperature shift factors for CER failure load

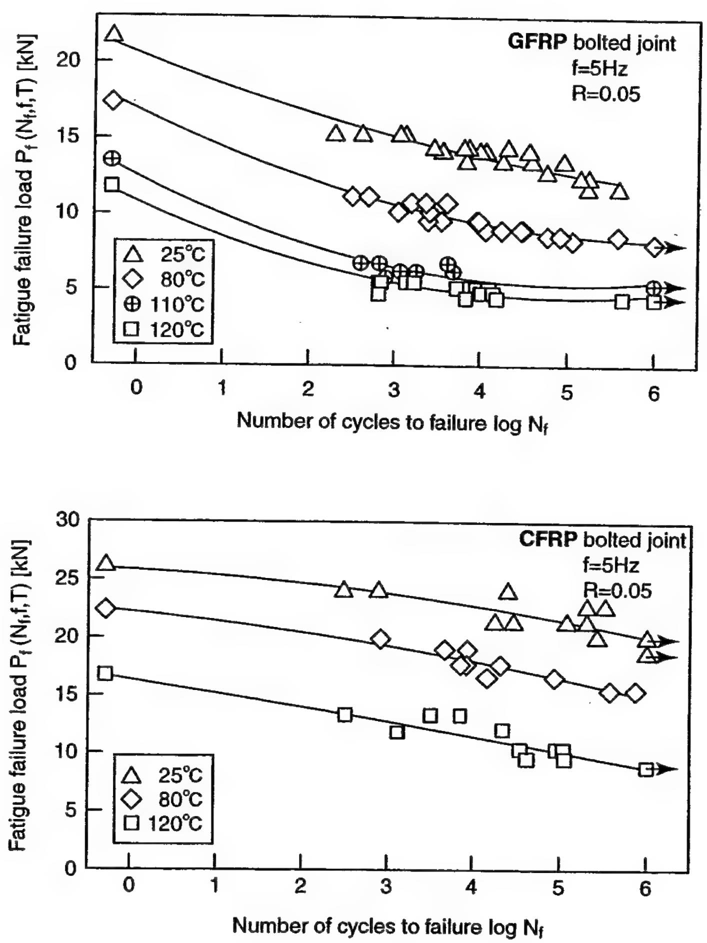


Fig. 12 Fatigue failure load versus number of cycles to failure of FRP bolted joint systems at f=5Hz

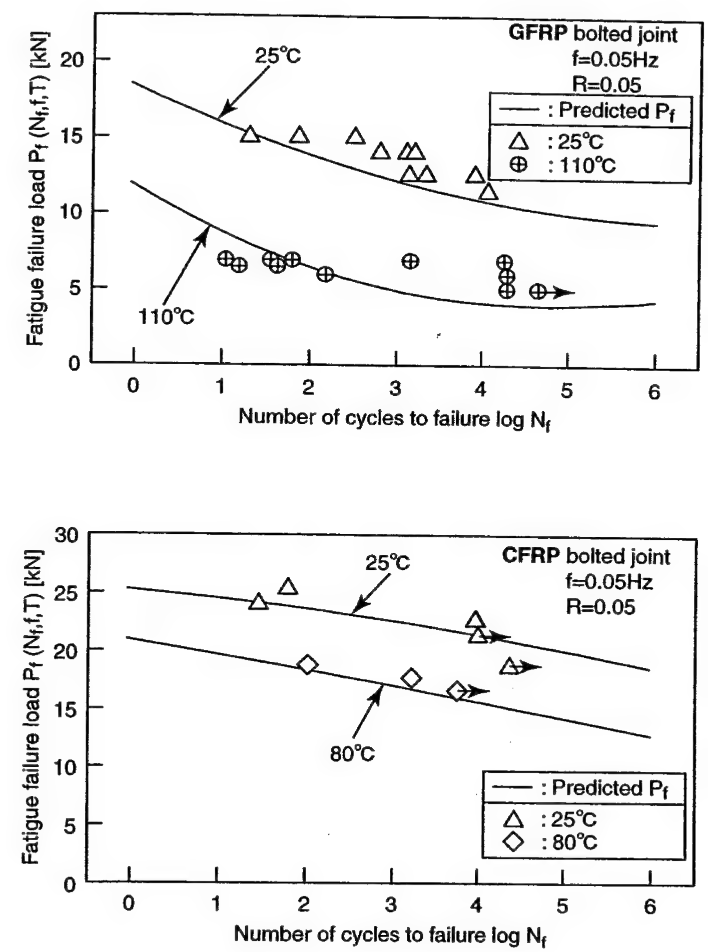


Fig. 13 Fatigue failure load versus number of cycles to failure of FRP bolted joint systems at f=0.05Hz

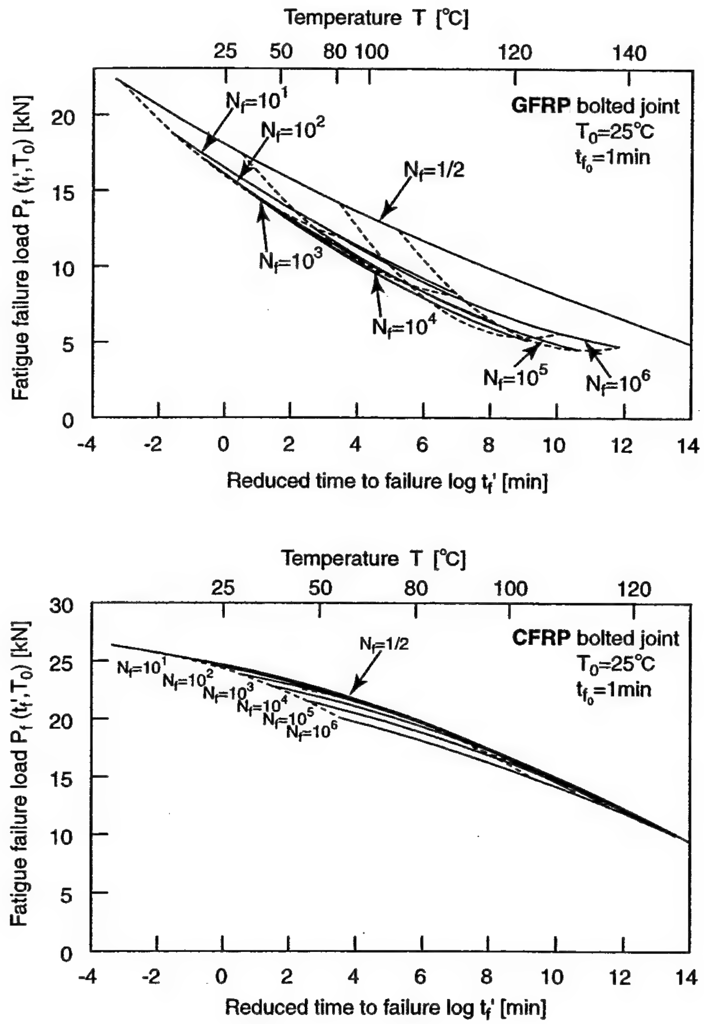


Fig. 14 Master curves of fatigue failure load

CONCLUSION

A prediction method for long-term fatigue strength of polymer composites at an arbitrary stress ratio, frequency, and temperature was proposed based on four hypotheses.

From our experimental finding:

-PAN-based CFRP and GFRP/metal joint meet the four hypotheses regardless the structural configuration and loading style.

-The master curves of fatigue strength for various CFRPs and GFRP/metal joints indicate respectively characteristic time and temperature dependent fatigue behavior.

-The fatigue failure load of CFRP/metal joint depends clearly on time and temperature, however this failure load decreases scarcely with increasing N_f.

Thermo-Mechanical Response of Composites at Cryogenic Temperatures

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THERMO-MECHANICAL RESPONSE OF COMPOSITES AT CRYOGENIC TEMPERATURES

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ABSTRACT

Advanced composites are being explored for structural applications at extremely low temperatures, for example in large cryogenic fuel tanks on NASA's Reusable Launch Vehicle and on the Air Force's Space Operations Vehicle. Exposure to these cryogenic temperatures can cause transverse microcracks in the composites due to thermal residual stresses brought on by the anisotropy in the composite ply coefficient of thermal expansion (CTE). Transverse cracking often results in a reduction in laminate stiffness and strength and changes in laminate CTE, and provides a pathway for the ingress of moisture or corrosive chemicals; in cryotanks, transverse cracking can cause leakage of the pressurized liquid fuel. The objective of this work was to develop a predictive capability for the onset of transverse cracking in composite laminates subjected to isolated or combined thermal and mechanical loads. The material system investigated was a carbon fiber-reinforced toughened epoxy composite, IM7/977-3. The thermomechanical properties required for the analysis were obtained from tests on $[0]_{8T}$, $[90]_{8T}$, and $[\pm 45]_{2S}$ laminates. These laminates were tested at a number of temperatures ranging from ambient down to -191°C, using a custom-built cryogenic chamber installed on a mechanical test machine.

Cross-ply laminate, with $[0_2/90_2]_S$ was used to experimentally determine the onset of transverse cracking under isolated or combined mechanical and thermal loads. Transverse cracking was detected from acoustic emission and the response of bonded strain gages, and confirmed from microscopic examination of polished specimen edges. Ply stresses were calculated for the corresponding conditions from laminated plate theory, using the appropriate experimentally generated thermomechanical properties and the applied load. The maximum stress failure theory was applied to predict failure. The analytical predictions were then compared with experimental results at temperatures of 23, −129, and -191°C, and the results are reported here.

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OBJECTIVES

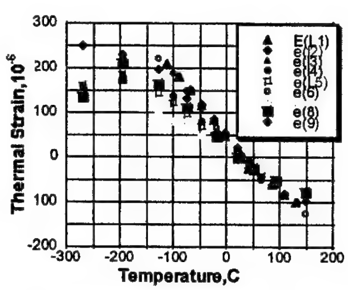
- **To study the thermomechanical behavior of composites at cryogenic temperatures**
- **To examine a predictive capability for the onset of microcracking in composite laminates subjected to combined thermal and mechanical loadings**

EXPERIMENT

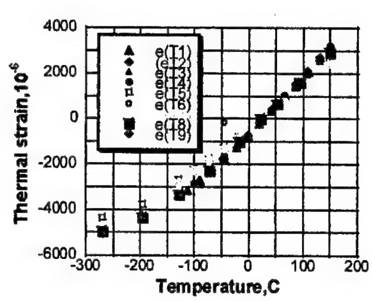
- Material Systems: IM7/977-3, IM7/5250-4, IM7/PETI5
- Laminates:
  - -Unidirectional: thermomechanical characterization
  - -Multidirectional: onset of microcracking
- Temperature range: -269 (-452) to 149°C (300°F)
- Designed and built test fixture and cryostat for cryogenic tests
- CTE measured using strain gages
- Material properties were determined at cryogenic temperatures
- Onset of microcracking determined under ambient test conditions from acoustic emission and at cryogenic temperatures from incremental step loading and unloading
- Microcracking confirmed in an optical microscope
- The onset of microcracking was predicted using lamination theory and failure theory

THERMAL STRAIN FOR MEASUREMENT OF CTE

AXIAL



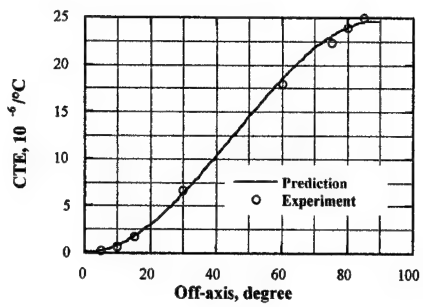
TRANSVERSE



Transverse sensitivity correction required for obtaining true thermal strain in axial direction: $\varepsilon = \varepsilon_a - K_t \cdot \varepsilon_t$

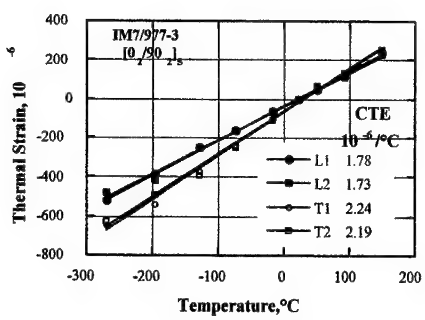
2

OFF-AXIS CTE



Prediction was made using the measured unidirectional CTEs

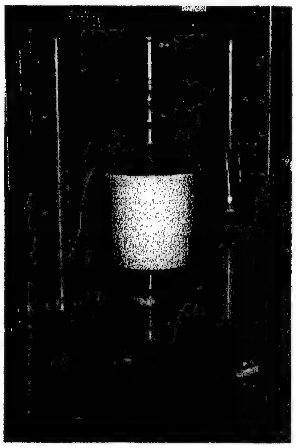
THERMAL STRAIN FOR $[0_2/90_2]_S$ LAMINATE



With respect to surface ply
L: parallel to fiber
T: perpendicular to fiber

Calculated CTE: 1.99 x10^{-6}/°C using unidirectional CTE values

MTS TEST FRAME FOR TESTING AT CRYOGENIC TEMPERATURES

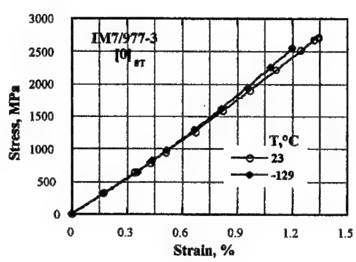


This simple device was initially used for testing at LN temperature.

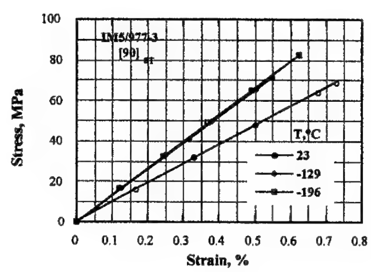
A custom built cryostat capable of testing down to LHe temperatures is being installed.

STRESS-STRAIN CURVES

AXIAL



TRANSVERSE



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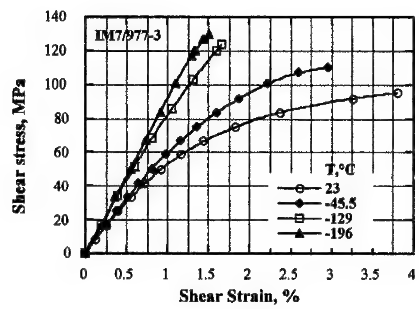
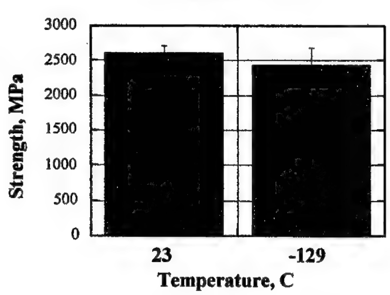
SHEAR STRESS-STRAIN CURVES



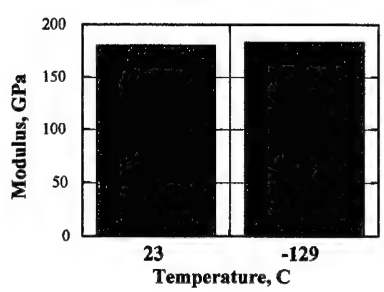
VARIATION OF LONGITUDINAL STRENGTH AND MODULUS

$[0]_{8T}$

STRENGTH



MODULUS



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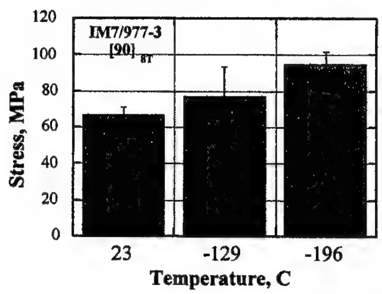
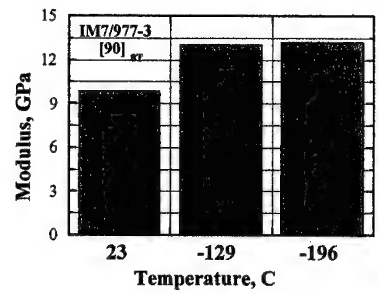
VARIATION OF TRANSVERSE STRENGTH AND MODULUS

$[90]_{8T}$

STRENGTH

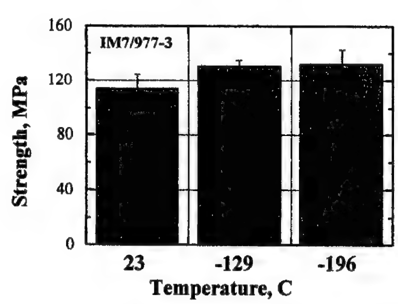


MODULUS

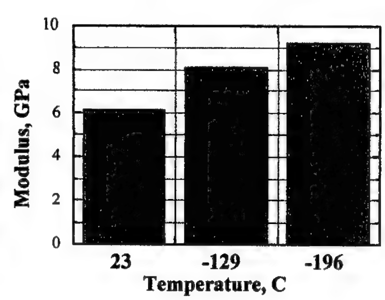


VARIATION OF INPLANE SHEAR STRENGTH AND MODULUS

STRENGTH



MODULUS



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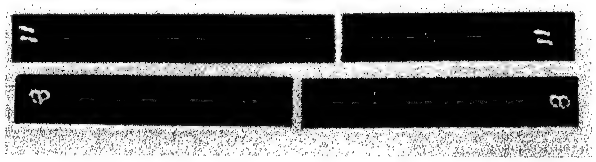
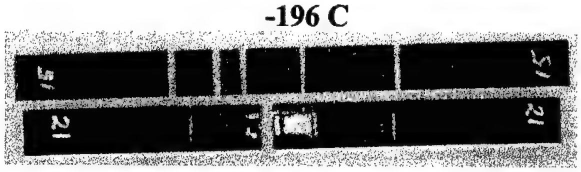
PHOTOGRAPHS of FAILED $[90]_{8T}$ SPECIMENS

23 C



-196 C

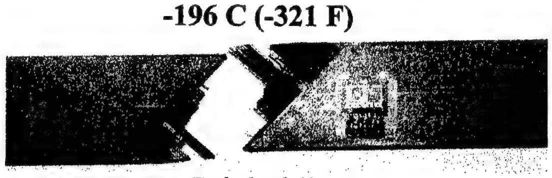


Multiple fracture at low temperatures

PHOTOGRAPHS OF OF FAILED $[\pm 45]_S$ SPECIMENS

23 C (73 F)

-196 C (-321 F)

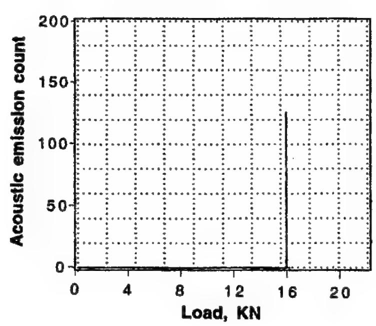


Brittle failure

VARIATION OF STRENGTH AND MODULUS

Laminate	Temperature C	Strength MPa	Coefficient of Variation, %	Modulus GPa
Longitudinal [0]8T	23	2,599	4.2	180
	-129	2,425	10.1	183
	-196	x	x	x
Transverse [90]8T	23	74.5	6.7	9.8
	-129	83.4	22.1	13.2
	-196	97.2	5.6	13.4
Shear [±45]2S	23	113.3	5.6	6.1
	-129	130.5	3.1	8.1
	-196	132.1	5.4	9.2

ACOUSTIC EMISSION RECORD FOR $[0_2/90_2]_S$ LAMINATE AT 23 C



The acoustic emission event indicates the occurrence of the first trasnverse crack

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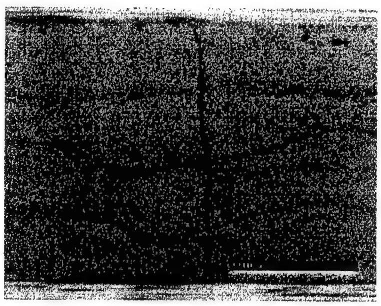
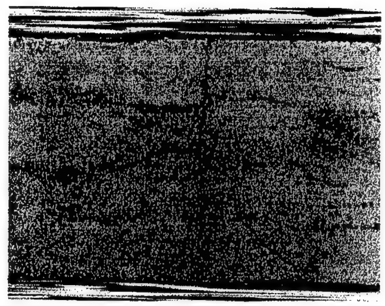
PHOTOMICROGRAPHS OF INITIAL MICROCRACKS

$[0_2/90_2]_S$

23 C (73 F)



-196 C (-321 F)



90° PLY STRESS AT ONSET OF MICROCRACKING FOR $[0_2/90_2]_S$ LAMINATE

Temperature °C	*Curing residual stress in 90 ply MPa	**Mechanical stress in 90 ply at cracking MPa	Total stress in 90 ply MPa	90 ply strength MPa
23	17.8	60.4	78.2	74.5
-129	45.6	52.3	97.9	83.4
-196	60.3	51.8	112.1	97.3

*Stress free temperature=163°C and moisture content=0.15 %
**Average of 4 specimens at -129C and 8 specimens at 23 and -196C

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SUMMARY

- Specimen alignment for transverse loading is critical at cryogenic temperatures
- Transverse strength and in-plane shear increased at low temperatures while strain to failure decreased; brittleness increased as the test temperature decreased
- The nonlinearity of the shear stress-strain curve decreased significantly at cryogenic temperatures
- Strain gages allow easy and accurate measurement of composite CTEs at cryogenic temperatures
- CTE decreased at cryogenic temperatures
- The stress level at the onset of transverse cracking decreased significantly at low temperature, due primarily to an increase in thermal residual stresses
- Further work needs to clarify the discrepancy between observed and calculate stress at onset of microcracking at cryogenic temperatures.

Durability Assessment of Polymer Matrix Composite Materials for Use on the Next-Generation SST at National Aerospace Laboratory

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Durability Assessment of Polymer Matrix Composite Materials for Use on the Next-Generation SST at National Aerospace Laboratory

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Introduction

The structures of the next-generation supersonic transport (SST) require the long-term durability of structural materials under a variety of conditions involving temperature, loads, and fluids, not only in constant states but also with cyclic fluctuations. Structural weight moreover must be drastically reduced to achieve commercial success requiring extensive use of high-temperature polymer-matrix composite materials.

The National Aerospace Laboratory (NAL) is carrying out joint research programs with five organizations to evaluate the long-term durability of high-temperature polymer-matrix composite materials nominated for use on the next-generation SST. The five organizations are the National Institute of Materials and Chemical Research, three major aircraft manufacturing companies, i.e., Fuji Heavy Industries, Ltd., Kawasaki Heavy Industries, Ltd., and Mitsubishi Heavy Industries, Ltd., and the Japan Aircraft Development Corporation.

The authors briefly introduce the test results obtained in our joint research programs in order to evaluate the effects of isothermal aging and thermal cycling on the strength degradation, and the bearing creep behavior of carbon/high-temperature polymer-matrix composite materials, referring to the three papers [1-3] published.

Effect of Isothermal Aging on Strength Degradation [1]

This study evaluated the effect of isothermal aging on the ultimate strength of G40-800/5260 and MR50K/MR2000N carbon/bismaleimide composite materials and a T800H/PI-SP carbon/amorphous thermoplastic-polyimide composite material. The hole-notched and unnotched panels, before being machined to specimens, were isothermally aged at 120°C and 180°C for up to 15,000 hours. Static tests at room and elevated temperatures before and after thermal aging provided the open-hole tensile, open-hole compressive, and short beam shear strengths.

In the case of the G40-800/5260 bismaleimide composite material, the degradation of open-hole tensile strength by isothermal aging at 120°C was not clear. Although the open-hole compressive strength at room temperature was not reduced by isothermal aging at 120°C, this strength at 120°C slightly decreased after isothermal aging of 15,000 hours. The latter fact was identical for the MR50K/ MR2000N bismaleimide composite material also. No degradation of open-hole compressive and SBS strengths was observed for the T800H/PI-SP thermoplastic-polyimide composite material after thermal aging at 120°C and 180°C up to 15,000 hours.

Effect of Thermal Cycling on Open-Hole Compressive Strength [2]

This study investigated the effect of thermal cycles encountered by an SST in service on the degradation of high-temperature polymer matrix composite materials. One cycle of thermal

cycling was designated as the sequence from room temperature (RT) to -54°C, up to +177°C, and back to RT. The retention time was 15 minutes each at the minimum and maximum temperatures. Different kinds of specimens were prepared for microcrack observation and static mechanical tests. Thermal cycling tests were conducted up to 10,000 cycles on IM7/PIXA carbon/thermoplastic-polyimide and IM7/K3B carbon/polyimide composite materials and up to 1,000 cycles on a G40-800/5260 carbon/bismaleimide composite material. At scheduled thermal cycles, transverse microcracks initiated on the sectional surface of the laminates were observed by using an optical microscope. Static mechanical tests provided the open-hole compressive strength before and after thermal cycles.

The open-hole compressive strength before and after thermal cycles did not change during the course of this study, though a lot of microcracks were found. Therefore, thermal cycles and the initiation of transverse microcracks did not affect the open-hole compressive strength.

Bearing Creep Behavior [3]

This study investigated the bearing creep behavior of a G40-800/5260 carbon/bismaleimide composite material. Bearing creep tests were carried out at 120°C, 150°C, and 180°C. Load levels for creep tests corresponded to 0.3, 0.4, 0.5 and 0.6 of the 4%-yield bearing strength. The torque of the bolt in bearing creep tests was adjusted to 3.5 kgf·cm (3 in·lb) using a torque wrench. The residual hole-deformation was used as an index of creep damage. The hole deformation was measured at scheduled creep hours after detaching the specimen from the test fixture. The creep test was then continued using a new set of a nut and a bolt. The tests provided the bearing tensile strength as a function of temperature, the hole deformation by creep up to 10,000 hours as a function of the load level and temperature, and the damage in longitudinal sections at the loaded-hole edges by bearing creep and bearing tensile tests.

The large deformation of the bolt hole was observed at high load levels and elevated temperatures, though the deformation was small under the condition of the low load level at 120°C. As the temperature rose, the hole deformation increased even at the low load level.

References

[1] Shimokawa, T., Hamaguchi, Y., Kakuta, Y., Katoh, H., Sanda, T., Mizuno, H., and Toi, Y., "Effect of Isothermal Aging on Ultimate Strength of High-Temperature Composite Materials for SST Structures," *Journal of Composite Materials*, Vol. 33, No. 12, 1999, pp. 1104-1118.

[2] Shimokawa, T., Katoh, H., Hamaguchi, Y., Sanbongi, S., Mizuno, H., Nakamura, H., Asagumo, R., and Tamura, H., "Effects of Thermal Cycling on Degradation of High-Temperature Polymer Composite Materials for the Next-Generation SST Structures," *Proceedings of the 9th US-Japan Conference on Composite Materials*, Japan Society for Composite Materials and American Society for Composites, Mishima, Japan, July 2000, pp. 355-362.

[3] Katoh, H., Shimokawa, T., Tsuda, H., Sakai, A., and Asagumo, R., "Bearing Creep Behavior of a Carbon/Bismaleimide Composite Material for the Next-Generation Supersonic Transport," *Proceedings of the 9th US-Japan Conference on Composite Materials*, Japan Society for Composite Materials and American Society for Composites, Mishima, Japan, July 2000, pp. 603-610.

Durability Assessment of Polymer Matrix Composite Materials for Use on the Next-Generation SST at National Aerospace Laboratory

Toshiyuki Shimokawa and Hisaya Katoh
National Aerospace Laboratory

For Presentation at the Composites Durability Workshop 2000
Tokyo, Japan, August 23, 2000

1

Introduction

Structures of the Next-Generation Supersonic Transport (SST)

Long-term durability of structural materials
Temperature, loads, and fluids
NASA HSCT: Mach 2.4, 177℃, 30,000 flights, 60,000 hours

Drastic reduction of structural weight

Extensive use of high-temperature polymer-matrix composite materials

2

Joint Research Programs

National Aerospace Laboratory (NAL) and five organizations:

National Institute of Materials and Chemical Research (NIMCR), aircraft manufacturing industries (FHI, KHI, and MHI), and Japan Aircraft Development Corporation (JADC)

The objectives are to evaluate the effects of isothermal aging and thermal cycling on the strength degradation, and the bearing creep properties of carbon/high-temperature polymer-matrix composite materials.

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Effect of Isothermal Aging on Strength Degradation

(1) Open-hole tensile strength vs. thermal aging time
(2) Open-hole compressive strength vs. thermal aging time
(3) Short beam shear strength vs. thermal aging time

4

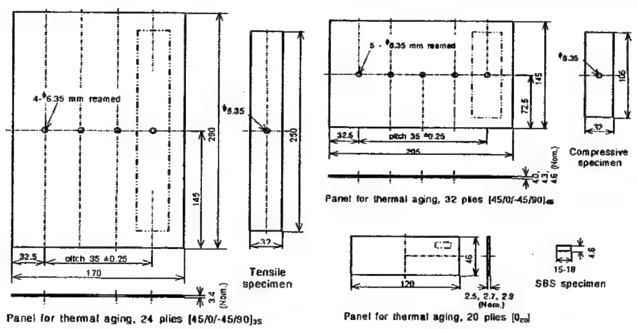

Fig. 1: Geometry of panels for isothermal aging and specimens tested; dimensions in mm.

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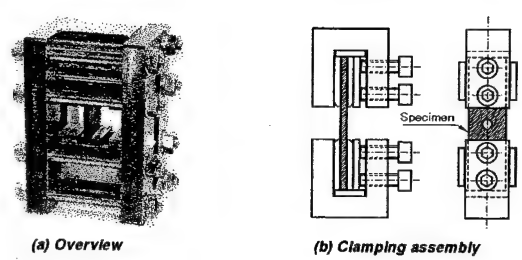

Fig. 2: Compression test fixture

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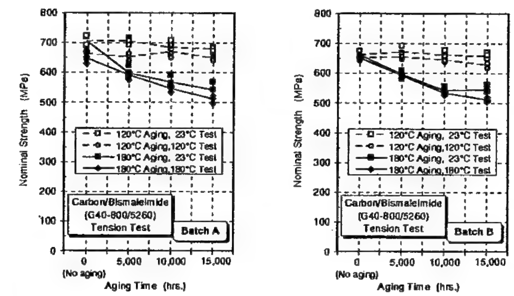

Fig. 3: Open-hole tensile strength of G40-800/5260 carbon/bismaleimide composite versus thermal aging time for two batches A and B.

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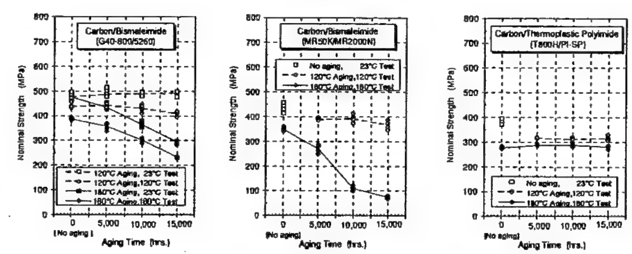

Fig. 4: Open-hole compressive strength versus thermal aging time for three kinds of carbon/high-temperature polymeric composites.

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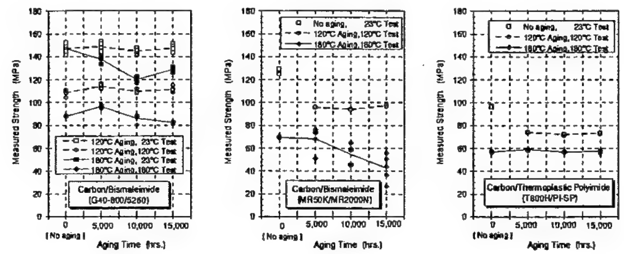

Fig. 5: Short beam shear (SBS) strength versus thermal aging time for three kinds of carbon/high-temperature polymeric composites.

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Effects of Thermal Cycling on Open-Hole Compressive Strength

(1) Number of microcracks initiated vs. thermal cycles

(2) Open-hole compressive strength vs. thermal cycles

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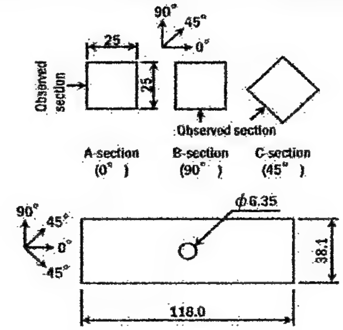

Fig. 6: Specimen configurations for microcrack observation and open-hole compression tests.

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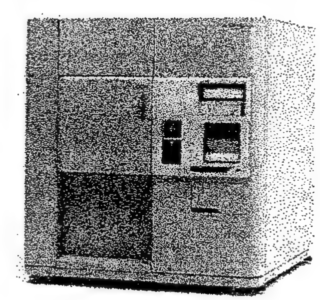

Fig. 7: Thermal cycling test system (TABAI ESPEC Co. TSA-70H).

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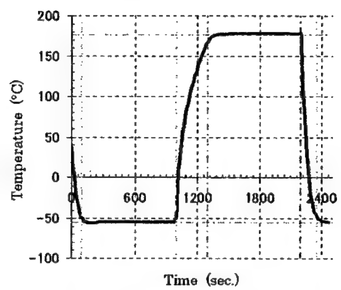

Fig. 8: Test thermal cycle measured in a specimen of the same size as that used for microcrack observation.

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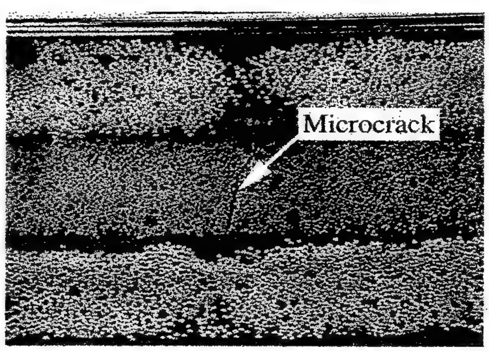

Fig. 9: A typical transverse microcrack.

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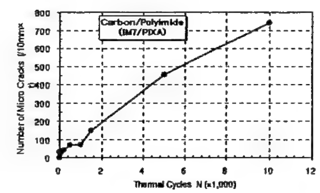

Fig. 10a: Number of microcracks initiated in the sectional area of 10mm×thickness as a function of thermal cycles (IM-7/PIXA).

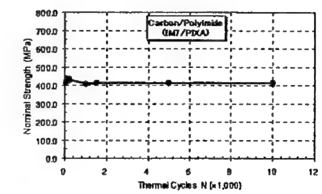

Fig. 11a: Open-hole compressive strength at room temperature before and after thermal cycles (IM-7/PIXA).

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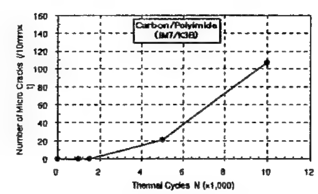

Fig. 10b: Number of microcracks initiated in the sectional area of 10mm×thickness as a function of thermal cycles (IM-7/K3B).

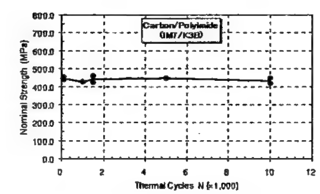

Fig. 11b: Open-hole compressive strength at room temperature before and after thermal cycles (IM-7/K3B).

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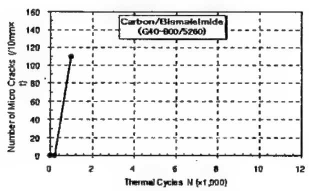

Fig. 10c: Number of microcracks initiated in the sectional area of 10mm×thickness as a function of thermal cycles (G40-800/5260).

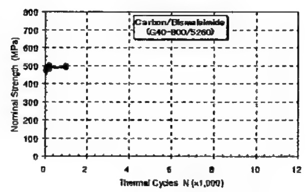

Fig. 11c: Open-hole compressive strength at room temperature before and after thermal cycles (G40-800/5260).

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Bearing Creep Behavior

(1) Load vs. hole deformation in bearing tensile tests
(2) Bearing tensile strength vs. temperature
(3) Hole deformation vs. creep testing time
(4) Hole deformation after 120 hours vs. load level

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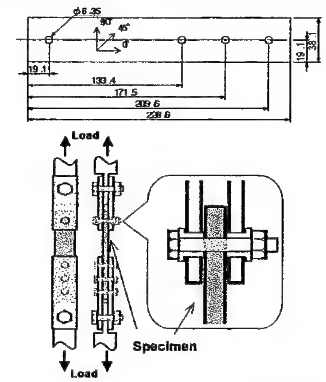

Fig. 12: Specimen configuration and bolt-loading apparatus, dimensions in mm.

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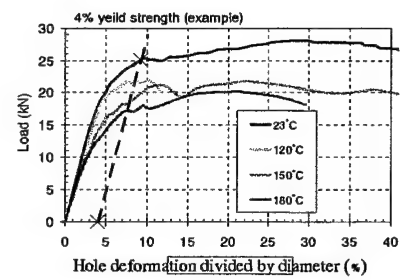

Fig. 13: Load versus hole deformation in bearing tensile tests.

20

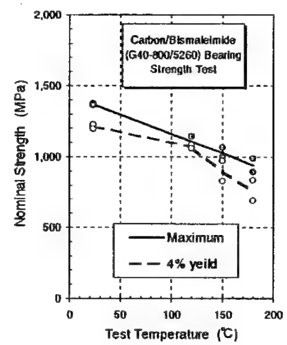

Fig. 14: Bearing tensile strength versus temperature.

21

Table I: Load levels of bearing creep tests.

Temperature (°C)	Maximum load (kN)	4% yeild load (kN)	Load (kN)			
			x 0.3	x 0.4	x 0.5	x 0.6
23	28.0	24.8				
120	22.6	21.9		8.7	10.9	13.1
150	21.1	18.3		7.3		11.0
180	19.2	15.6	4.7	6.2	7.8	9.4

22

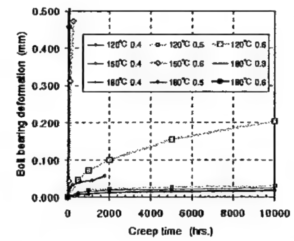

Fig. 15: Hole deformation versus testing time.

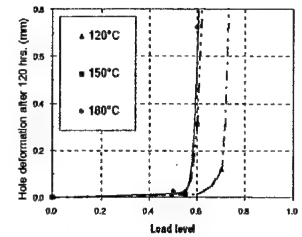

Fig. 16: Hole deformation after 120 hours versus load level.

23

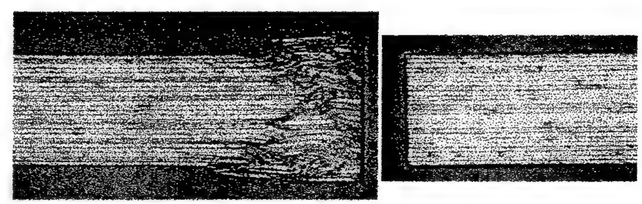

Fig. 17: Photomicrography of longitudinal cross sections at the hole edge in a bearing creep test.

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Status of Project on Advanced Composite Materials for Transportation in Japan

Yasuhiro Yamaguchi*

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Minoru Noda

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Status of Project on Advanced Composite Materials for Transportation in Japan

Y.Yamaguchi , A.Sakamoto and M.Noda

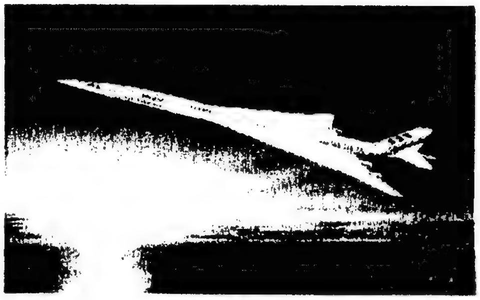
R&D Institute of Metals and Composites for Future Industries (RIMCOF),
3-25-2, Minato-ku, Tokyo 105-0001, Japan

Abstract

The research and development project on advanced composite materials for transportation has been performed since September, 1998 as a 5-year project, being sponsored by the Ministry of International Trade and Industry.
This project aims to develop innovative design and manufacturing technologies simultaneously cost reduction and reliability improvement of polymer matrix composite structures for transportation. This paper introduces briefly the purpose and contents, and current activities of the program.

CDW '00

Status of Project on Advanced Composite Materials for Transportations in Japan




Y.Yamaguchi_A.Sakamoto,M.Noda,

R&D Institute of Metals and Composites for Future Industries (RIMCOF)

RIMCOF

Introduction

- **To reduce fuel consumptions of transportation-vehicles ,**
  weight savings of their structures required
- **Polymer-matrix-composites**
  the most promising materials to be applied for
- **However their applications limited**
  because of high costs and poor design-basis

RIMCOF

Introduction

To develop

low-cost manufacturing and innovative design technologies for future transportation systems

The 5 years/33M$ R&D project on Advanced Composite Materials for Transportations started in 1998 under MITI contract

RIMCOF

Themes

1. Aerospace Transportation Systems

Application Technologies of High-Temperature Polymer Composites (ACDMT by JADC)

2. Advanced High-Speed Train

High-Productive Technologies of Large-Scale Composite Structures (by TORAY)

3. Joining Technologies and Improvements of Flame-Retardation of Polymer Composites (by HITACHI)

4. F.R. on Damage-Tolerant Design (by U.T.&O.U.)

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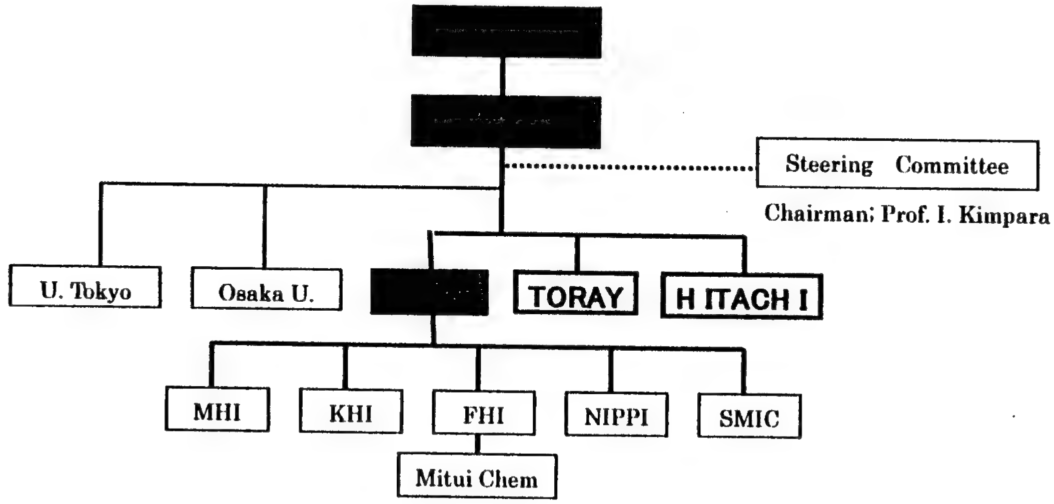
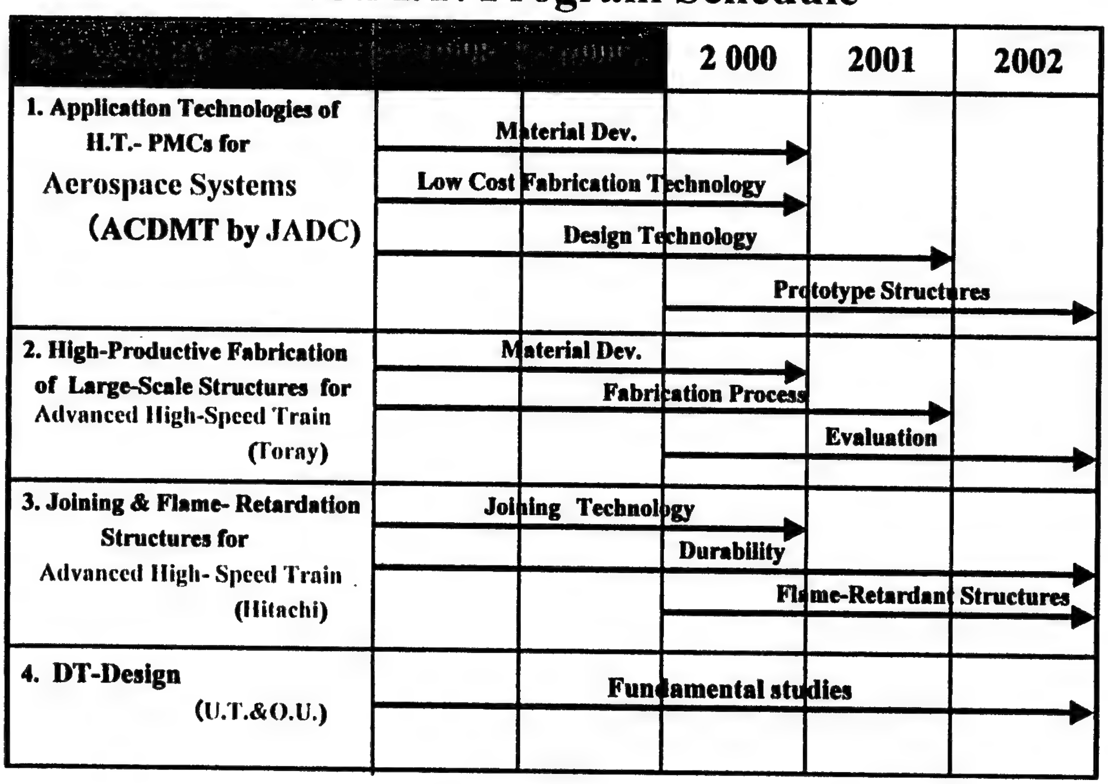
Functional Organization



A.C.M.T. Program Schedule



Aerospace Transportation Systems

Application Technologies of High-Temperature Composites
A.C.D.M.T.(by JADC)

(1) Material Development

(2) Low-cost Fabrication Technology

(3) Design Technology

(4) Prototype Structures

(5) Typical Results up to 1999

RIMCOF

Advanced High-Speed Train

High-Productive Technologies of Large-Scale Composite Structures

(by Toray)

(1) Material Development

(2) Fabrication Process

(3) Evaluation

(4) Typical Results up to 1999

RIMCOF

Advanced High-Speed Train

Joining Technologies and Flame-Retardation of Composite Structures

(by Hitachi)

(1) Joining Techniques

(2) Durability Characterization

(3) Flame-Retarded Structure

(4) Typical result up to 1999

RIMCOF

Conclusion

Current Status of the National Project

"A.C.M.T."

- For Aerospace Transportation Systems, Application Technologies of High-Temperature Polymer Composite
- For Advanced High-Speed Train, High-Productive Fabrication, Joining&Flame-Retardation Technologies

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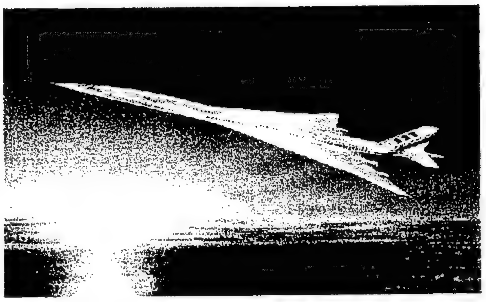
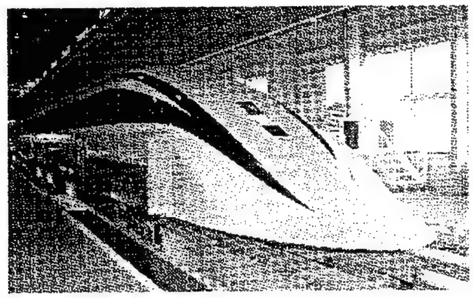
CDW '00

Status of Project on Advanced Composite Materials for Transportations in Japan





Y.Yamaguchi, A.Sakamoto, M.Noda,

R&D Institute of Metals and Composites for Future Industries (RIMCOF)

RIMCOF

Outline

1. Introduction
2. Themes and Organization
3. For future Aerospace Transportation Systems
   High-Temperature Polymer Composites
4. For Advanced High-Speed Train
   (1) High-Productive Technologies of
   Large-Scale Composite Structures
   (2) Joining Technologies and Flame-Retardation of
   Composite Structures
5. Conclusion

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Introduction

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- Polymer-matrix-composites
  the most promising materials to be applied for

- However their applications limited
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Introduction

To develop
low-cost manufacturing and innovative design technologies
for future transportation systems

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Advanced Composite Materials for Transportations
started in 1998 under MITI contract

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Themes

1. **Aerospace Transportation Systems**

   Application Technologies of High-Temperature Polymer Composites (ACDMT by JADC)

2. **Advanced High-Speed Train**

   High-Productive Technologies of Large-Scale Composite Structures (by TORAY)

3. **Joining Technologies and Improvements of Flame-Retardation of Polymer Composites (by HITACHI)**

4. **F.R. on Damage-Tolerant Design**

   (by U.T.&O.U.)

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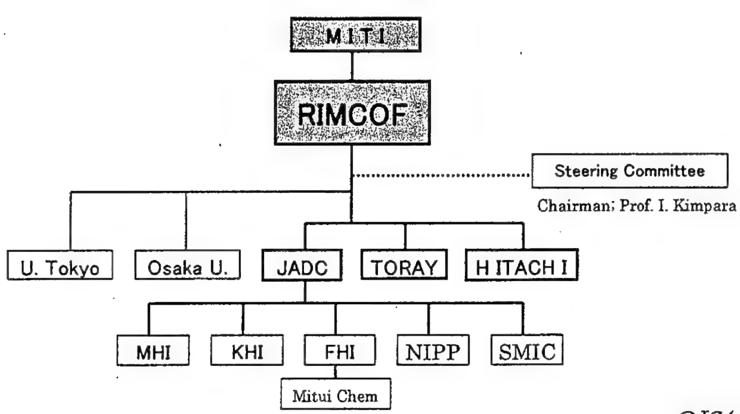
Functional Organization



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A.C.M.T. Program Schedule

FY	1998	1999	2 000	2001	2002
1. Application Technologies of H.T.- PMCs for Aerospace Systems (ACDMT by JADC)	Material Dev.				
	Low Cost Fabrication Technology				
	Design Technology				
			Prototype Structures		
2. High-Productive Fabrication of Large-Scale Structures for Advanced High-Speed Train (Toray)	Material Dev.				
	Fabrication Process				
			Evaluation		
3. Joining & Flame- Retardation Structures for Advanced High- Speed Train (Hitachi)	Joining Technology				
	Durability				
			Flame-Retardant Structures		
4. DT-Design (U.T.&O.U.)	Fundamental studies				

Aerospace Transportation Systems

Application Technologies of High-Temperature Composites A.C.D.M.T.(by JADC)

(1) Material Development

(2) Low-cost Fabrication Technology

(3) Design Technology

(4) Prototype Structures

(5) Typical Results up to 1999

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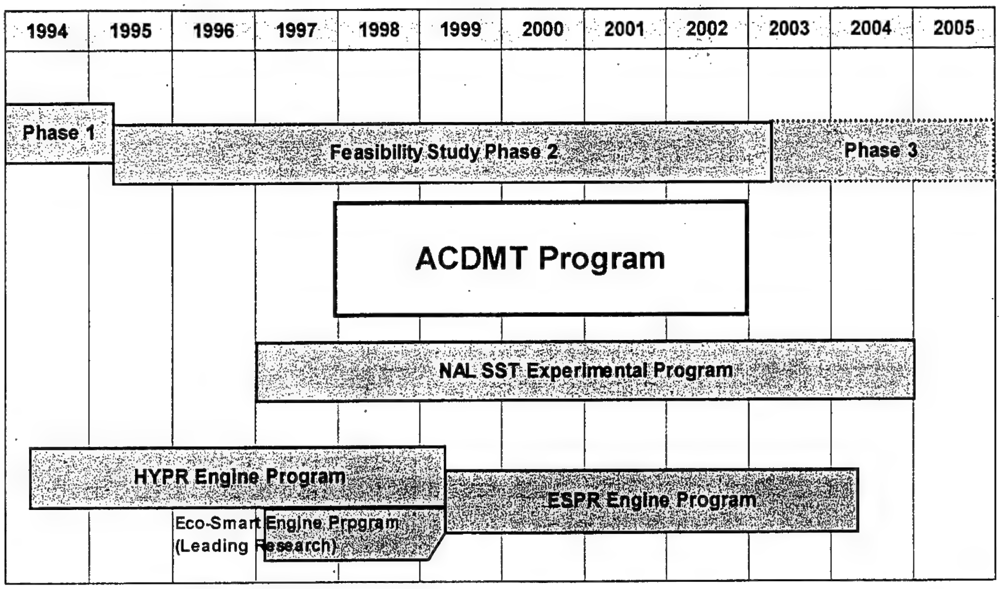
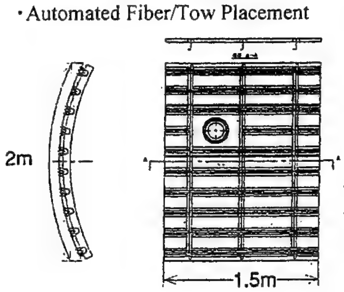
Japanese Supersonic Research Program

Program Schedule

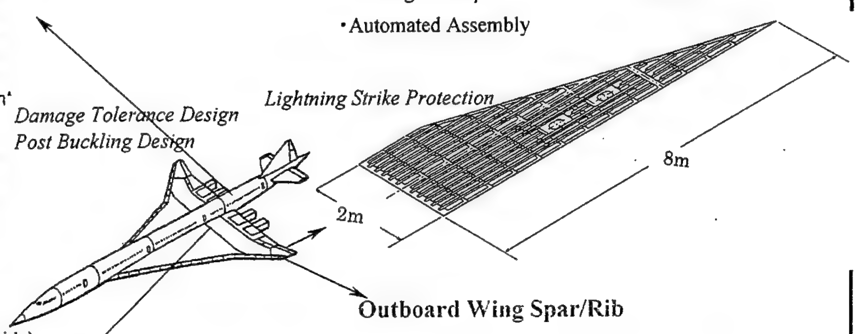


ACDMT Program Overview

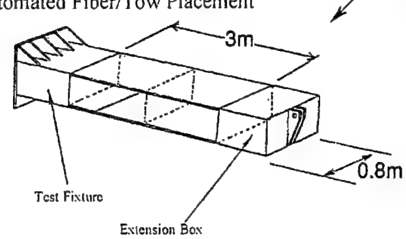
Aft Fuselage Panel (MHI)
- PETI-5 (Thermoset Polyimide)
- Automated Fiber/Tow Placement



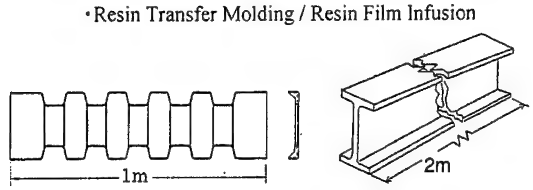
Outboard Wing Cover Panel (KHI)
- 5260 (Bismaleimide)
- Automated Fiber/Tow Placement
- Tooling Concept for Minimum Distortion
- Automated Assembly



Inboard Wing Box (FHI)
- PIXA Family (Thermoplastic Polyimide)
- Automated Fiber/Tow Placement



Outboard Wing Spar/Rib
- 5250-4-RTM (Bismaleimide)
- Resin Transfer Molding / Resin Film Infusion



Rib: RFI (Cloth Preform) (NIPPI)

Spar: RTM (FW Preform) (SMIC)

ACDMT Program Logic

(Advanced Composite Design and Manufacturing Technology)

Affordable High Temperature Composite Technology Basis

for 1) 20 percent Process Cost Reduction* and
2) 30 percent Weigh Reduction**

* 1998 High Temperature Composite Technology Base
** 1970 Concord Aluminum Structure Base

Subcomponent Development

Low Cost Process

Preliminary Design Criteria

Material

- PIXA Family
- PETI-5
- 5260
- 5250-4-RTM

Process

- Automated Fiber/Tow Placement
- RTM/RFI
- Tooling Concept for Minimum Distortion
- Automated Assembly

Design Data

- Damage Tolerance Design
- Post Buckling Design
- Honeycomb Panel Joints
- Lightning Strike Protection

Material Development

- Thermoplastic Polyimide
  IM600/PIXA

- Thermosetting Polyimide
  MR50K/PETI-5

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Low-Cost Fabrication Technology

- **Tow-Place/Direct Consolidation**
  IM600/PIXA T.P.Polyimide
- **Fiber/Tow Placement**
  MR50K/PETI-5 Polyimide
  IM600/5260 BMI
- **RTM/RFI**
  IM600/5250-4 BMI

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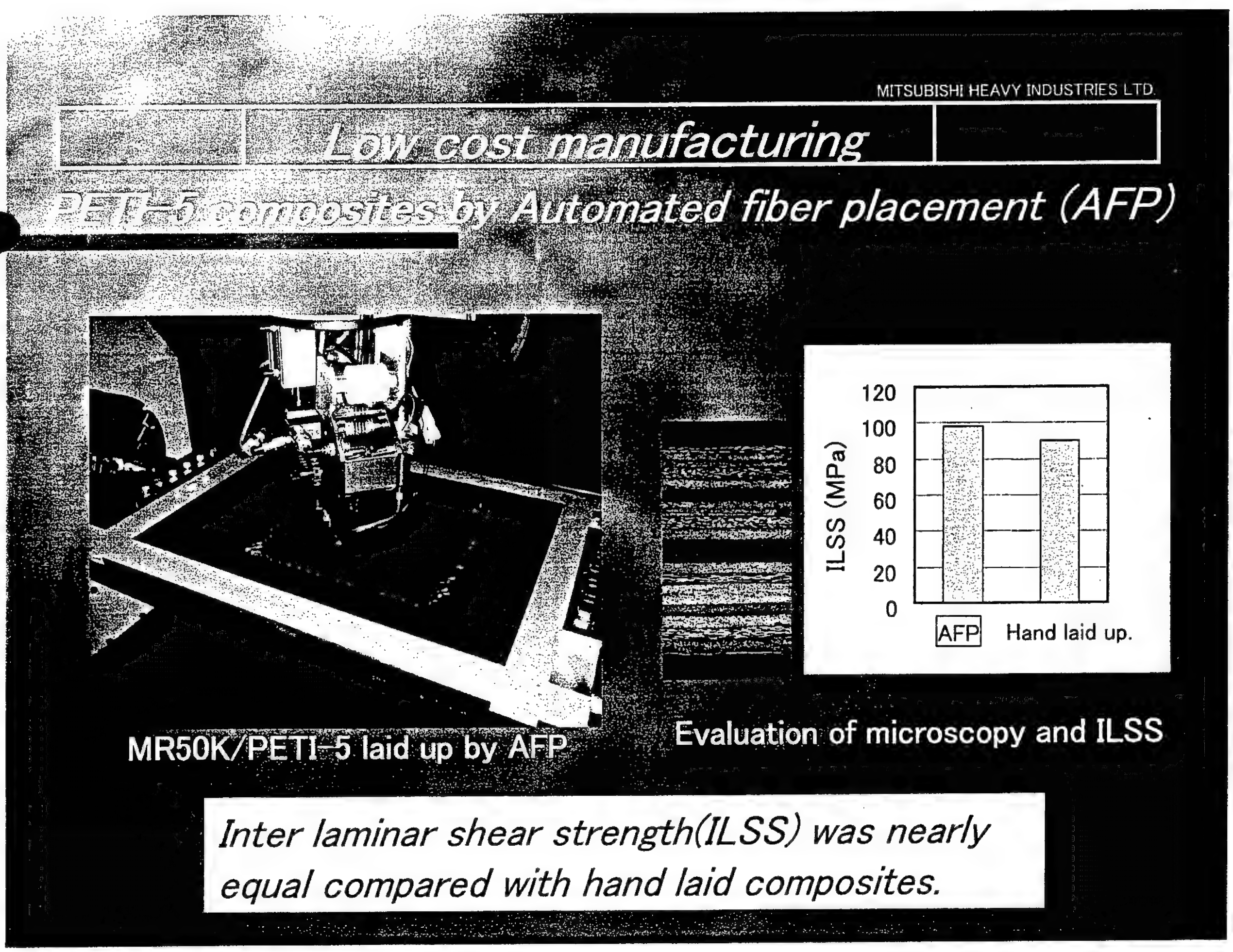
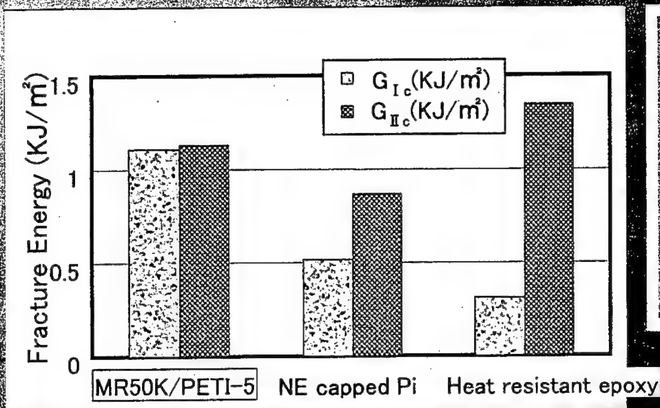
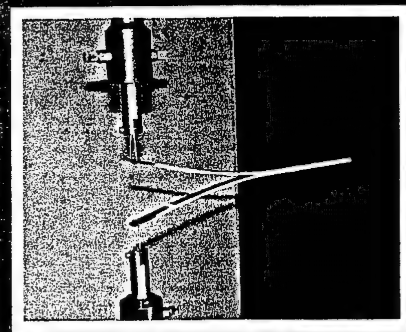


PETI-5 composite's merit

PETI-5 composites mechanical properties

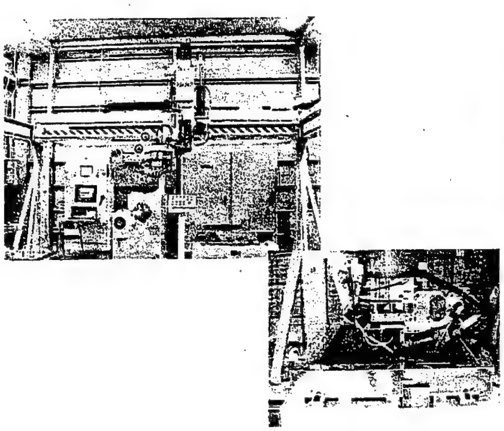




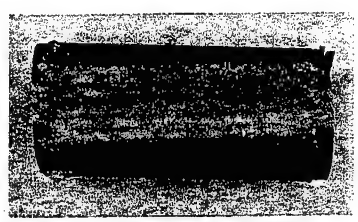
Fracture energy of UD composites

MR50K/PETI-5 has excellent toughness

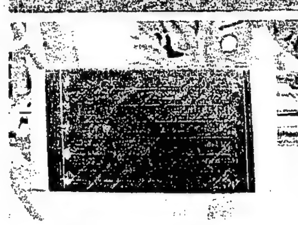
Automated Fiber/Tow Placement



Typical Machine Introduced



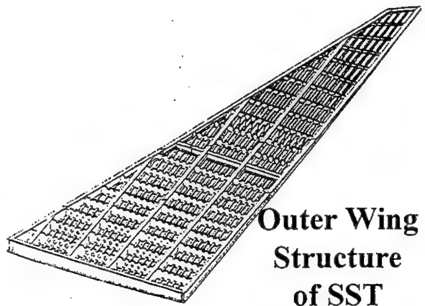
Cylinder of IM600/PIXA-M



Triangle Pole of Epoxy Composite

Typical Trial Products

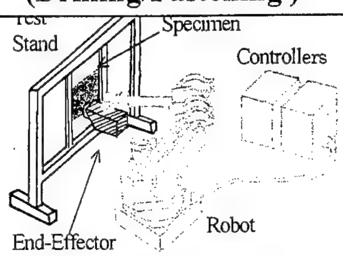
Low Cost Approach for Composite Wing Structure



Automated Fiber/Tow Placement for Structural Details

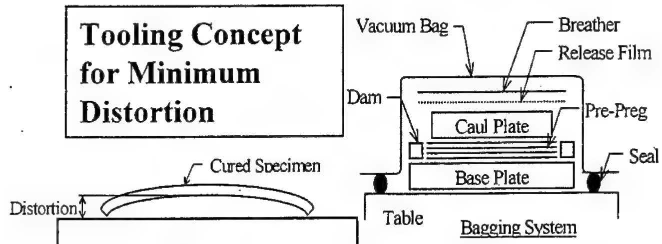
Constructed Fiber-Placement Machine

Automated Assembly (Drilling/Fastening)



End-effector set on a Industrial Robot Arm

Tooling Concept for Minimum Distortion



Experimental Research and Analysis

Advanced High-Speed Train

High-Productive Technologies of Large-Scale Composite Structures

(by Toray)

(1) Material Development

(2) Fabrication Process

(3) Evaluation

(4) Typical Results up to 1999

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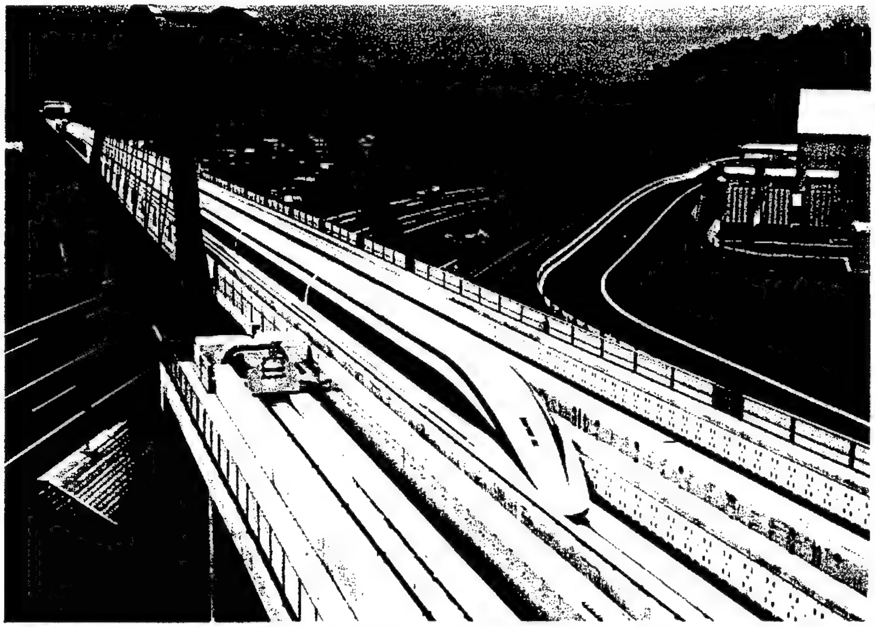


Linear Motor Car Systems

in Yamanashi Test Course (Max. Speed 550km/h)

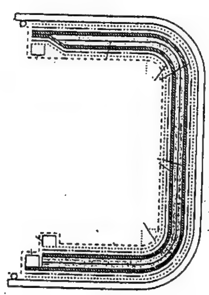
High-Productive Technologies of Large-Scale Composite Structures

High-Speed Fabrication

V-RTM

High-Speed Resin Transfer-Impregnation

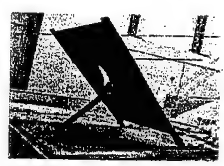
[XYwise → Zwise]

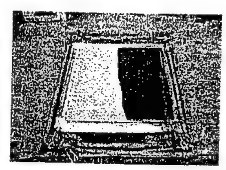


Advanced Matrix-Resin

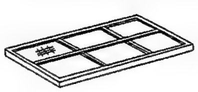
[Property]
- High-Modulous
- Non-Flamable

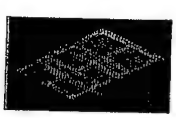
[Processability]
- Cure-Controllable
- High-Flow

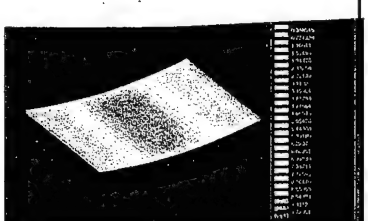




Design & Analysis

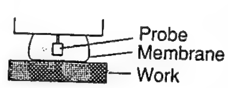


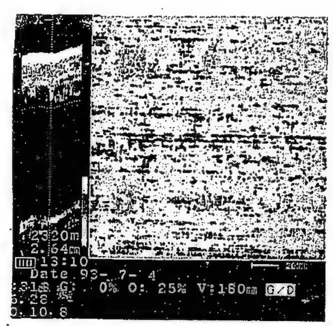




Inspection & Evaluation

Features
- Ultrasound
- Work Not in Water
- High Speed & Large Area Scanning



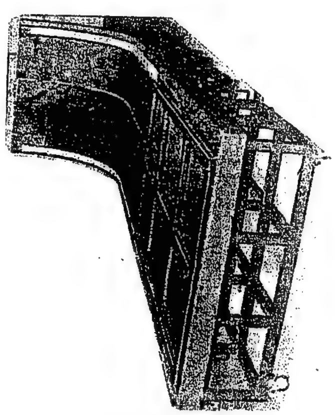


Research on matrix resins for large-scale VARTM

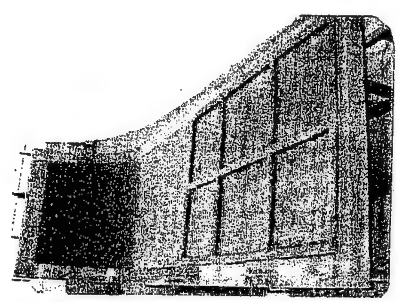
1. Requirements
   (1) Fire safe properties (Ignition time, Heat Release Rate, Smoke density)
   (2) Fabrication friendly properties (Viscosity, Void free, Curing conditions)
   (3) Mechanical properties (Elastic modulus, Toughness, Void free)

	Mechanical property	Fabrication friendly property			Less-flammability	Total point
	Elastic modulus(MPa)	Weight decrease during cure	Viscosity (@ R.T.)	Reactivity (<100℃)	Material combustion test for railroad (JAPAN)	
Epoxy resin	3.4	0.0	○	○	×	×
Phenolic resin	3.3	25.4	○	[redacted]		○
Benzoxazine resin	5.4	7.7	×	△	△	×
Cyanate ester resin	3.0	[redacted]	○	△	○	○
Bismaleimide resin	4.1	4.5	×	×	○	×

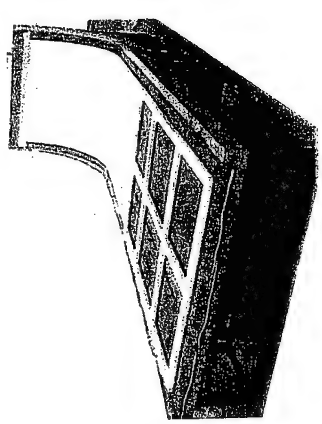
→ Candidates : Phenolic resin & Cyanate ester resin



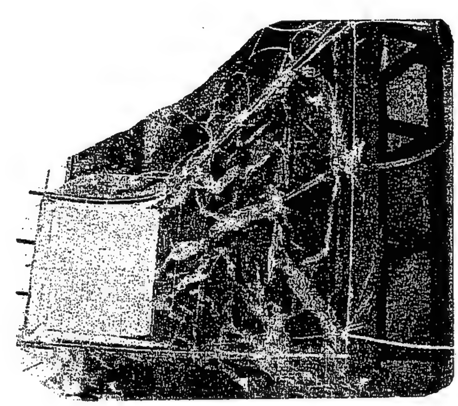
Fiber-Preform



After Cure

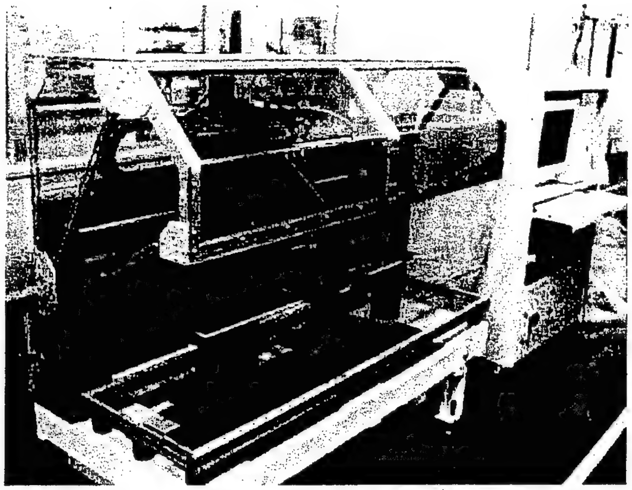


Foam-Core



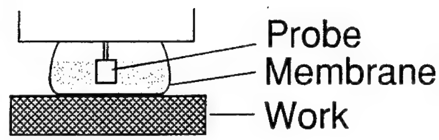
Resim Transfer

NDT for Large Scale Composite Structures



Features

- Ultrasound
- Work Not in Water
- High Speed & Large Area Scanning



Advanced High-Speed Train

Joining Technologies and Flame-Retardation of Composite Structures

(by Hitachi)

(1) Joining Techniques

(2) Durability Characterization

(3) Flame-Retarded Structure

(4) Typical result up to 1999

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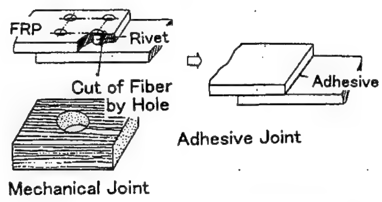
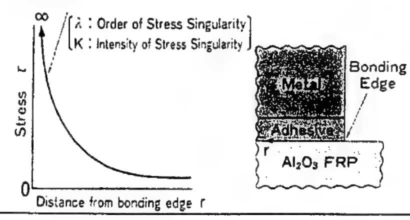
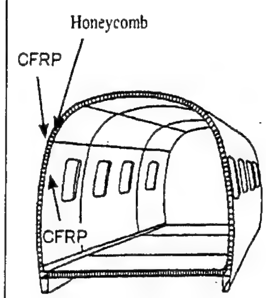
Application Technology of FRP on High Speed Train Car Body

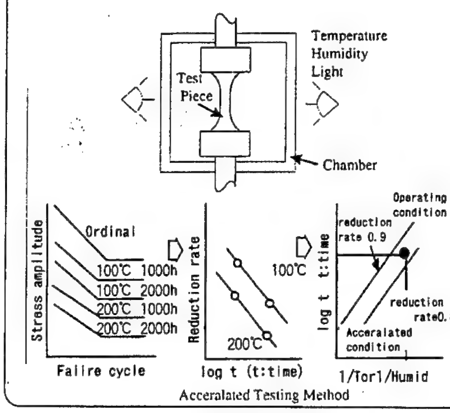
Strength Design of Joint Structure



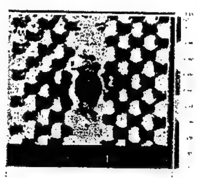




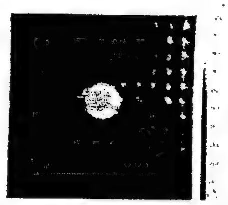
Environmental Strength Reduction



Fault·Damage Evaluation Method



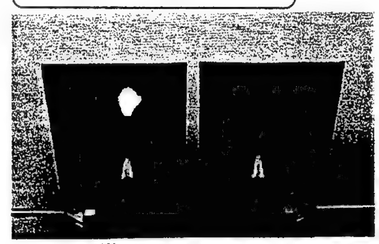
Stress Distribution



Thermal Distribution

Stress Distribution

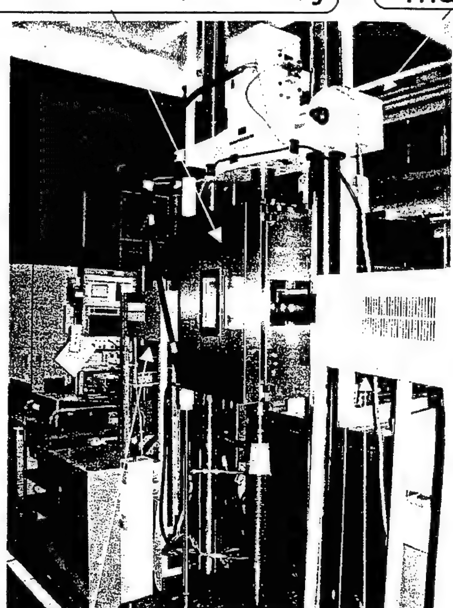
Nonflammable FRP



Evaluation Mmethod for Environmental Degradation of FRP (Temperature, Humidity, Light)

Furnace Controling temparature and humidy

Fatigue test machine



Light No. 1 Light No. 2

Furnace controling environment

Tab. Spesification

Size (mm)	400×600×350
Temparature	−60～300℃
Humidy	20%～95% Ref. Fig. of Under
Light	250KLx ×2

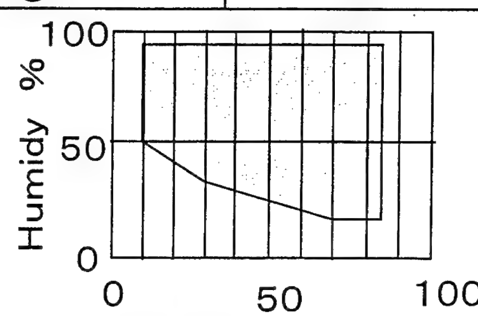
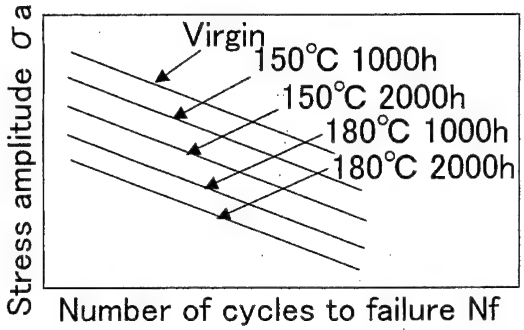
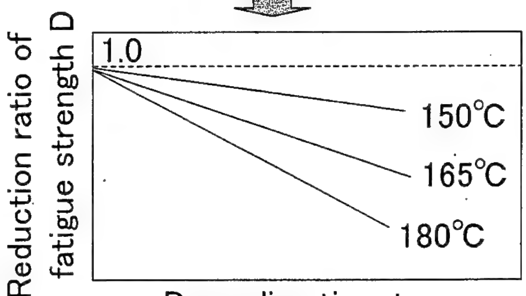


Fig. Control range of humidy

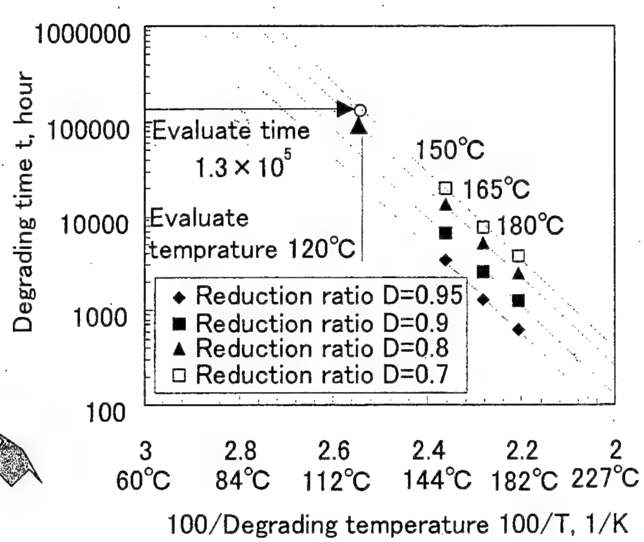
Evaluation Method of Thermal Degradation



Fatigue strength after thermal degradation



Reduction ratio of fatigue strength

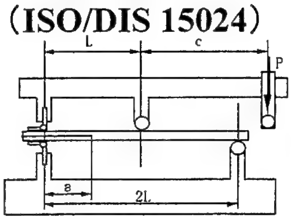


Arrhenius plots of fatigue strength reduction

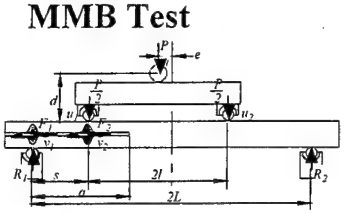
Approach

Experimental

Mode I
DCB Test
(ISO/DIS 15024)

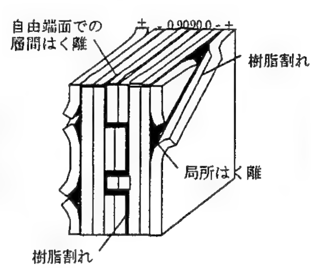


Mixed Mode
MMB Test

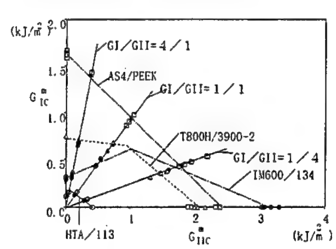


Mode II
4 ENF Test

Modeling

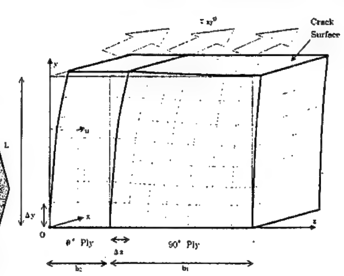


Damage Model

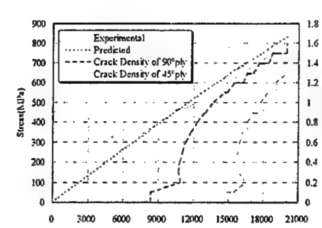


Mixed Mode Criterion

Computational



Numerical Method



Damage Tolerant Design

Conclusion

Current Status of the National Project "A.C.M.T."

- For Aerospace Transportation Systems, Application Technologies of High-Temperature Polymer Composite
- For Advanced High-Speed Train, High-Productive Fabrication, Joining&Flame-Retardation Technologies

RIMCOF

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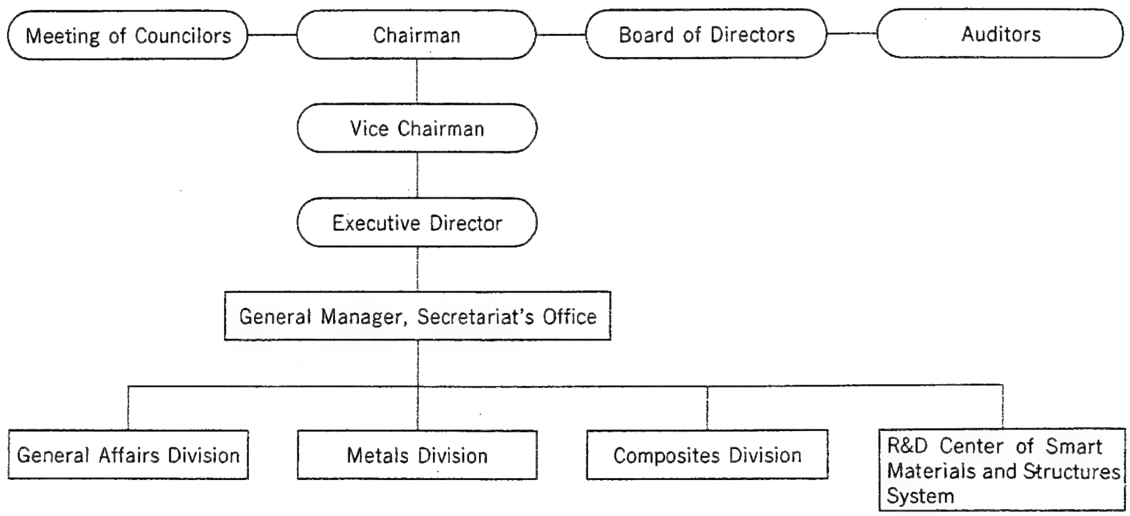
Organization



Assets, accounts and amount of operations

RIMCOF is an incorporated foundation and its constitutional assets amount to ¥71,750,000 as of April 1999. RIMCOF's major operations are from commissioned research and development projects, based on the Scientific Technology Develoment for Industries that Creates New Industries planned by AIST. Including other operations, RIMCOF's total operations amount to ¥2.8 billion (fiscal year 1999).

Major operations (Fiscal 1999)

1. New Energy and Industrial Technology Development Organization(NEDO)
   (1) Super Metal Technology(Technology for creating nanostructured bulky materials and amorphous bulky materials)
   (2) Smart Materials and Structural Systems
   (3) Ultra-low Core Loss Materials for Pole-Mounted Transformers
2. Ministry of International Trade and Industry(MITI)
   (1) Advanced Composite Materials for Transportation System
   (2) Materials Database of High Temperature Structural Composite Materials
3. Japan Standards Association(JSA)
   Evaluation Methodology for Long Term Durability of High Temperature Composite Materials
4. The Japan Machinery Federation
   Joining Technologies of Advanced Composite Materials for Aerospace Systems

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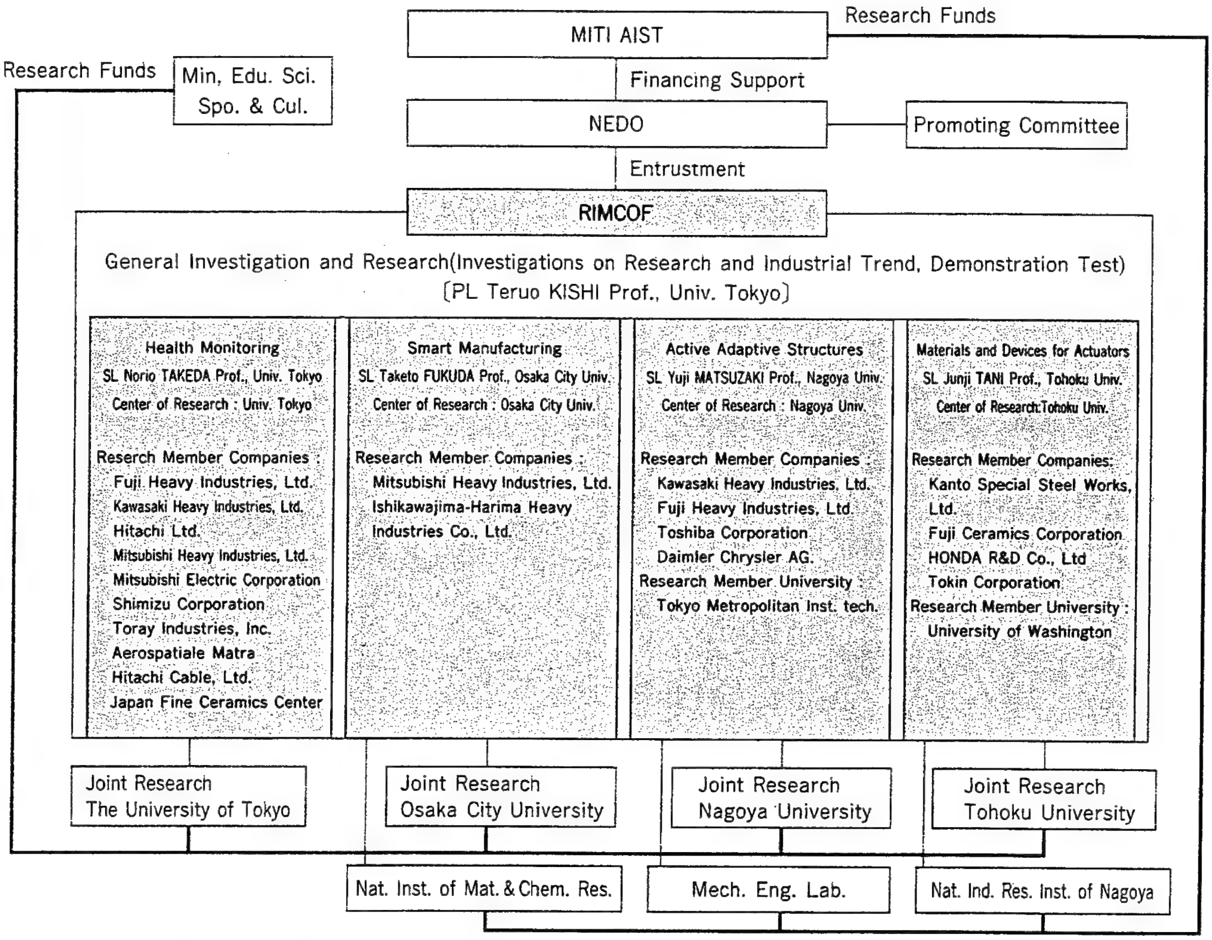
Smart Materials and Structural Systems

Organization of R&D

Our Institute has been earnestly carrying this project proposed during 5 years from April 1998 to March 2004 as the first theme for the "Academic Institutions Centered Program" under the "Industrial Science and Technology Frontier Program" enacted in 1998. It stands on the basic knowledge and the ideas rich in originality of the universities to create innovative technologies and develop new advanced fields for industry. The implementing organization has been established to form the network linking universities, private enterprises and national research institutes, as shown below.

Corresponding to this, RIMCOF has installed "R&D Center of Smart Materials and Structural System" to manage the project as a whole for promoting tight collaboration of the related agencies and members.



Organizational System for Smart Materials and Structural Systems Project.

Necessity for R&D

Composites provide a number of potentials and degrees of freedom for materials design aiming at high strength, creation of new functions and their various combinations and so on. Smart Materials and Structural Systems, whose mother structures consist of composites, indicate exactly the direction of development of materials engineering for the future, as it represents a big change in function from only"support" up to "act", which will open an innovative materials application technology by integrating structural, functional and information properties as a whole. Such a new paradigm of technology will contribute much to human and society through the creation of new industries related to human frontier to space, high-speed transportation, earthquake-resistant and disaster-preventing construction, etc.

Target of R&D

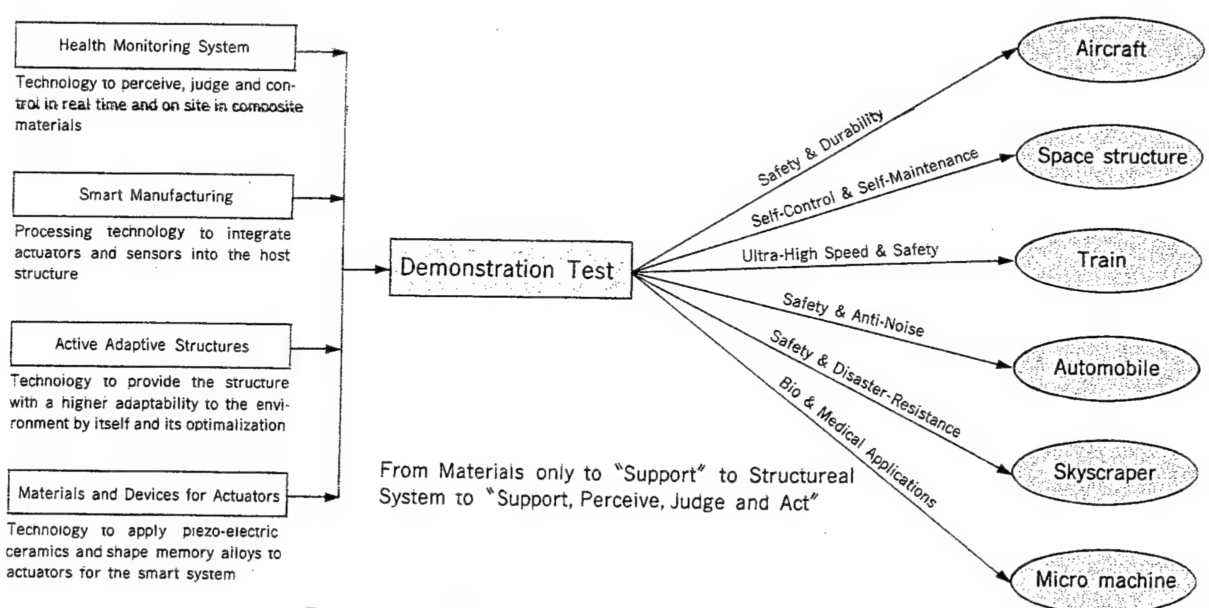
・The project intends to develop basic technologies of advanced materials and structure systems with smart and intellectual functions by integrating structural materials (likened to bone), sensor materials and devices (nerve) in the form of fiber, foil and film, actuator materials and devices (muscle), and the data processing and control ability (brain).

・To attain this objective, the research centers of university carry out researches concerning four elemental fields of technology such as health monitoring, smart manufacturing, active adaptive construction, and actuator materials and devices. On the basis of R&D results, demonstration experiments will be performed to verify the possibility of industrial application and commercialization.

Expected Effects of R&D

The project will bring us a drastic change of paradigm in materials utilization from only "material structure support" to a "positive comprehensive materials system", that is, a system to "support, perceive, judge and act".

It is expected to provide diverse and extensive contributions, as shown below in such industrial areas as aircraft, space, high speed trains, automobiles, highways, energy-saving process. It also realizes the higher quality of life by developing a new frontier of human activity, architecture and construction technologies with disaster-preventing capability, fail-safe applications of technology, as well as extended applications to the medical treatment and the environmental problems.



Four Main Fields of Research and Development for Smart Materials and Structural Systems and Applications of Their Results

3 .ヘルスモニタリング技術の研究開発

Research and Development Structural HealthMonitoring Technology

軽量複合材料を中心とする構造システムの安全性・信頼性を確保し、設計・製造からメインテナンス・修理までのライフサイクルコストを低減するために構造システムの構造健全性、耐久性を評価し、かつ保証する方法の確立が求められています。

本研究は、構造システムのリアルタイム自己検知・診断、および損傷制御を行うヘルスモニタリングシステムを開発することを目的とし、次の３つの主なテーマを設定しています。

1) 高性能センサシステム技術の開発
2) 構造健全性自己診断・損傷制御システム技術の開発
3) モデル構造、部分実構造への適用化技術の開発

センサ技術としては、細径光ファイバセンサの開発、形状記憶合金箔埋込みによる損傷抑制技術の開発、電気伝導性最大歪み記憶スマートパッチの開発などを行い、航空機、人工衛星、高速車両、高層建物などへの応用展開を目指します。

The structural health monitoring group is aiming to develop a health monitoring system which allows a real-time damage detection and self-diagnosis as well as control in lightweight composite structures. Such a system is expected to reduce life-cycle costs ranging from design and fabrication to maintenance and repair. The main research themes are:

1) Development of high-performance sensor system technology
2) Development of self-detection and diagnosis system technology for structural integrity
3) Development of application technology for a model and actual mechanical structures.

The following technologies are being developed : small diameter optical fiber sensors, composite laminates which can suppress damage by embedding shape-memory alloy films, and maximum strain "smart patches" which memorize the electrical conductivity in a composite.
Such technologies will be applicable to such fields as aircraft, satellites, high-speed trains and large-scale civil infrastructure.

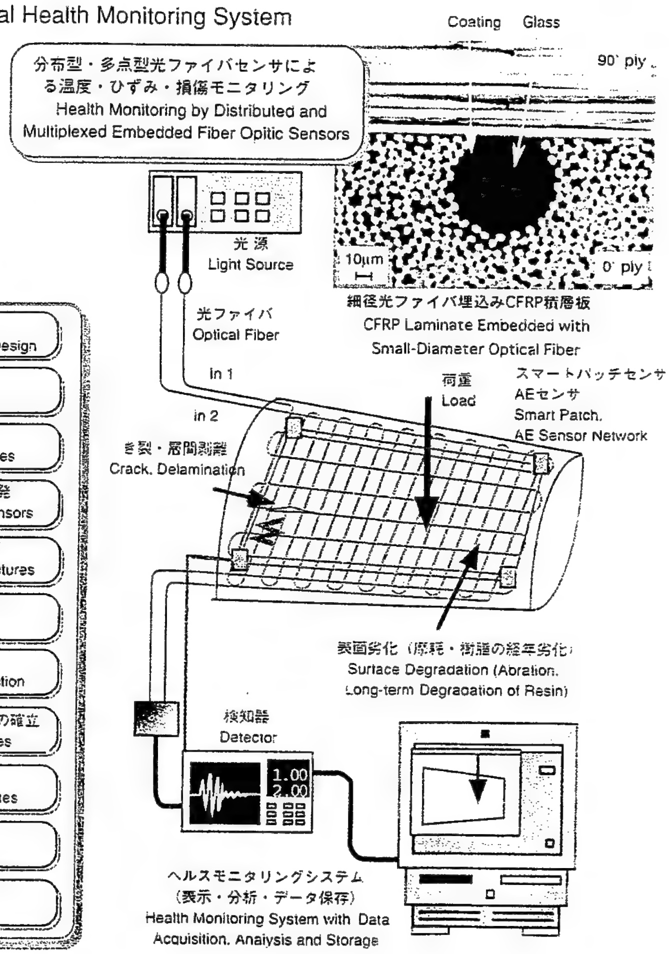
ヘルスモニタリングシステムの研究開発　R&D in Structural Health Monitoring System

研究開発目標 Objective of R&D

（1）高性能センサシステム技術の開発
Development of high-performance sensor system technology
（2）構造健全性自己診断・損傷制御システム技術の開発
Development of a damage detection and self-diagnosis system based on micro-mechanical damage identification
（3）モデル構造、部分実構造への適用化技術の開発
Development of application technology for model structures

新規開発技術 R &D Under Development

- 損傷許容設計のための複合材料微視的損傷検出技術の開発
  In-situ Detection of Microscopic Damage in Composite Laminates for Damage Tolerance Design
- 細径光ファイバセンサの開発と広温度範囲コーティング技術開発
  Development of Small-Diameter Fiber Optic Sensors and High-Performance Coating
- 複合材料埋込み光ファイバセンサによる衝撃損傷パラメータ同定技術の確立
  Impact Damage Detection Using Embedded Fiber Optic Sensors in Composite Laminates
- 分布型BOTDRセンサ、ブラッグ格子光ファイバセンサひずみ測定統合システムの開発
  Strain Measurement System Using Distributed BOTDR Sensors and Multiplexed FBG Sensors
- 人工衛星損傷許容設計のための光ファイバセンサによる歪・損傷ヘルスモニタリング
  Strain and Damage Monitoring by Fiber Optic Sensors for Damage-Tolerant Satellite Structures
- 高層建築物常時ヘルスモニタリングセンサシステムの開発
  On-site Monitoring System for High-Story Building Structures
- 光透過・光反射型センサシステムによる半透明複合材のヘルスモニタリング
  Health Monitoring of Semi-Transparent Composites Using Light Transmission and Reflection
- 統合定量化アコースティックエミッションセンサ網による複合材料構造健全性の制御技術の確立
  Integrated Acoustic Emission Sensor Network for Structural Integrity of Composite Structures
- 形状記憶箔・線を用いた損傷自己検知・制御型複合材料システムの開発
  Damage Detection and Suppression Using Embedded SMA Films in Composite Laminates
- 炭素繊維破断型スマートパッチの開発と定量化技術
  Development of Smart Hybrid Patch Sensors Using Carbon Fibers
- 複合材料母構造への導電性付与による損傷・破壊検知材料の研究開発
  Damage Detection Using Electrically-Conductive Matrix in Composites



Recent Advances in Pitch-Based Carbon Fibers and Their Composites

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"Recent Advances in Pitch-based Carbon Fibers and Their Composites"

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Pitch-based carbon fiber covers a wide range of Young's moduli. High thermal conductivity fibers and high impact resistance carbon fibers have been developed by the Nippon Graphite Fiber Corporation (NGF, http://plaza6.mbn.or.jp/~NGF/) from mesophase pitch and from isotropic pitch. The properties of these fibers and their composites are discussed.

1. High thermal conductivity fibers from mesophase pitch [1], [2], and [3]

The pitch-based carbon fibers show higher Young's modulus and higher thermal conductivity than PAN-based carbon fibers due to their highly developed graphite structures. This is the reason pitch-based carbon fibers are suitable for space applications, which require high stiffness, light weight and high thermal conductivity. It is also important that these high modulus/high thermal conductivity fibers have excellent handleability and excellent cost performance for making fabric for an expanding range of practical applications. The developed fibers, Granoc YS-90A and YS-95A have thermal conductivity of 500 and 600 W/m·K, a tensile modulus of 880 and 920 GPa, a diameter of 7 microns and good handleability. The handleability of the developed carbon fibers was evaluated by the clip test to reveal that fibers can be applied to thin spread fabric for satellite parts.

The mechanical properties of CFRP using 4-harness satin fabric and unidirectional prepreg were measured, and both laminates presented almost the same values, which were about 90% of the rule of mixture. The thermal conductivity in-plane direction of both laminates corresponded to the calculated values of the fiber performance. In regard to out-of-plane direction, the thermal conductivity of the 1-ply fabric laminates was higher than that of the 2-ply 0°/90° unidirectional laminates for all fiber volume fractions.

As a result, it was found that the developed fibers were quite suitable for high thermal application fields.

2. High impact resistance carbon fibers from isotropic pitch [4], [5], and [6]

The developed fiber, Granoc XN-05 has a Young's modulus of 55 GPa, and a compressive strain of 1.8 % which is higher than that of PAN-based carbon fiber. The mechanical properties of CFRP reinforced with XN-05 have been studied, and these fibers allows much more deformation against compressive stress.

CFRP with the toughened epoxy resin system has been used in the aircraft field, and the resin system helps improve the impact properties. However, in case of CFRP made with carbon fiber with a high compressive strain, it is expected that the carbon fiber itself helps improve the impact properties.

By applying a thin layer of this fiber on the surface of PAN-based carbon fiber laminates, the energy absorption of the hybrid laminates in the impact test was largely increased. The static flexural properties of these laminates were evaluated in the three point bending mode. Then, the impact resistance was evaluated with drop impact test in 3 point bending. The hybrid laminates showed excellent impact resistance under the velocity of up to 20 m/s. It was found that XN-05 prevented the compressive fracture of the PAN-based carbon fiber.

Finally the impact test in ballistic mode were carried out. QI laminates were tested in CAI (Compression after impact) by Dr. Ishikawa at National Aerospace Laboratory, and $0^{o}/90^{o}$ laminates were evaluated in ultra high-speed impact tests(600-1300m/s) using steel impactor of 2mm diameter by Dr. Tanabe at Tokyo Institute of Technology. XN-05 helps decrease the damage area of CFRP in these impact tests.

In conclusion, it is expected that the XN-05 should contribute to the improvement of the impact properties of CFRP with PAN-CF by preventing the compressive fracture. Therefore, the high impact resistance carbon fiber has the potential to be used in industrial fields in addition to sporting goods.

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2. N. Kiuchi, K. Ozawa, T. Komami, O. Katoh, Y. Arai, T. Watanabe and S. Iwai, SAMPE Technical Conference, 30, 68 (1998)

3. A. Fukunaga, H. Ohno, H. Takashima and S. Uemura, SAMPE Japan International Symposium, 2, 129 (1991)

4. N. Kiuchi, Y. Sohda, S. Takemura, Y. Arai, H. Ohno and M. Shima, SAMPE Japan International Symposium, 133-136 (1999)

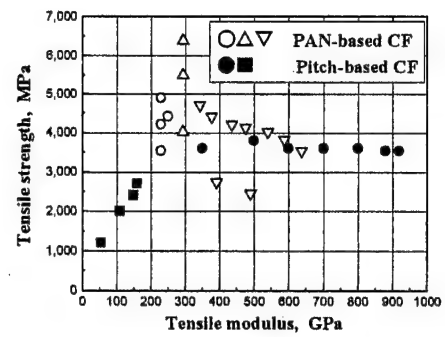
5. S. Takemura et al., 44th International SAMPE Symposium, 1999, p782-793

6. N. Kiuchi, Y. Sohda, Y. Arai, H. Ohno and M. Shima, SAMPE Technical Conference, (2000)

Recent Advances in Pitch-based Carbon Fibers and Their Composites

Yoshio Sohda and Tetsuji Watanabe
Central Technical Research Laboratory
Nippon Mitsubishi Oil Corporation

COMPOSITES DURABILITY WORKSHOP 2000
CDW'00
August 22-23, 2000
Tokyo Office, Kanazawa Institute of Technology

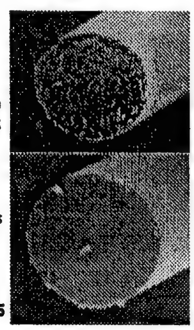


High thermal conductivity fibers from mesophase pitch

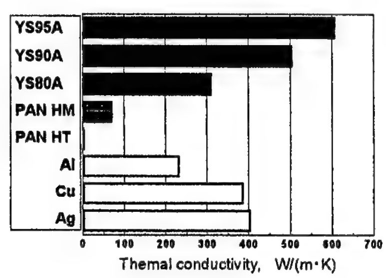
Granoc YS-90
Granoc YS-95

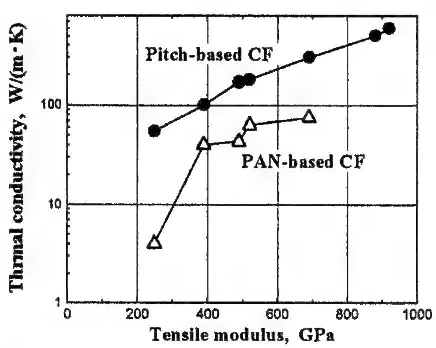
High impact resistance carbon fibers from isotropic pitch

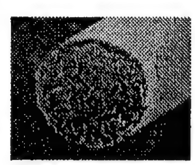
Granoc XN-05

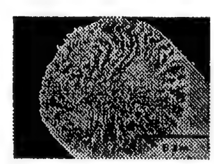


Nippon Graphite Fiber Corp.







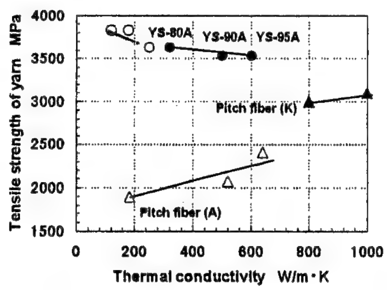


YS-90A T.C.= 500 W/m·K
YS-95A T.C.= 600 W/m·K

7 μm diameter

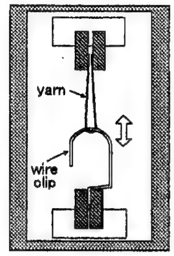
Conventional fiber

10 μm diameter



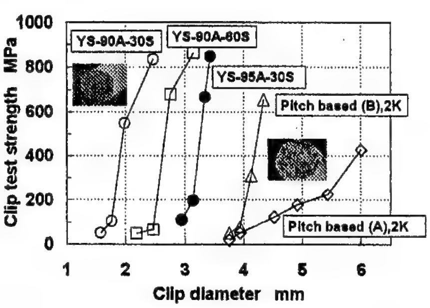
Relation between thermal conductivity and tensile strength of yarn

Evaluation of yarn handleability
Clip test



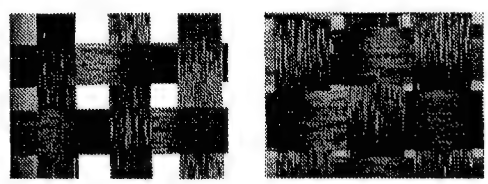
Specimen length: 100 mm
Testing speed : 2 mm/min

Clip strength
=Breaking load/cross-sectional area



Clip test strength of carbon fibers

YS-90A and YS-95A
for
ultra thin fabric fabrication



Before spreading

After spreading

Mechanical properties of CFRP using YS-90A-30S

	UD-laminates	0°/90° laminates	Spread fabric laminates
Tensile strength MPa modulus GPa	2040 540	950 290	970 300
Flexural strength MPa modulus GPa	670 420	430 270	430 270

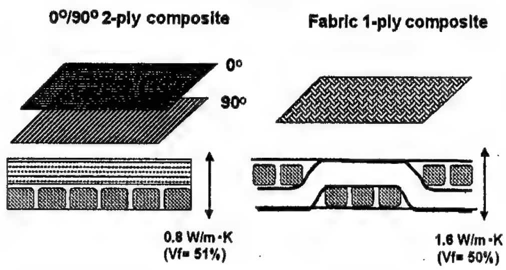
Fabric: SF(4HS) -YS90A-200 (AFW: 200 g/m²)

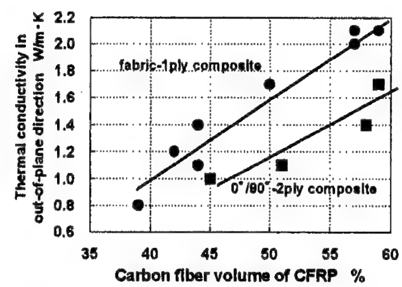
Thermal conductivity of CFRP using YS-90A-30S in plane direction

Prepreg	Specification	CFRP (Vf: 60%)		T.C. of CF (calculated) W/m・K
		X dir. W/m・K	Y dir. W/m・K	
UD-P.P.	0°/90°: 16 ply	151	145	504 (X dir.) 483 (Y dir.)
Spread Fabric -P.P.	13 ply	145	154	484 (X dir.) 514 (Y dir.)

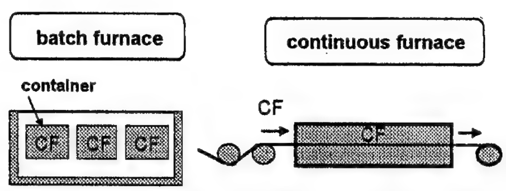
YS-90A: 500 W/m・K

Thermal conductivity of CFRP using YS-90A out-of-plane direction

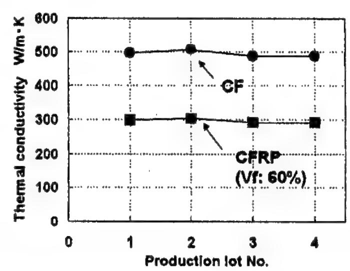




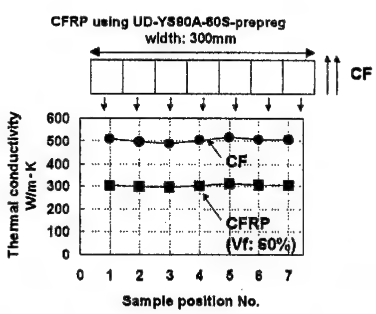
Out-of-plane thermal conductivity as a function of Vf



Schematic diagram of graphitization furnaces



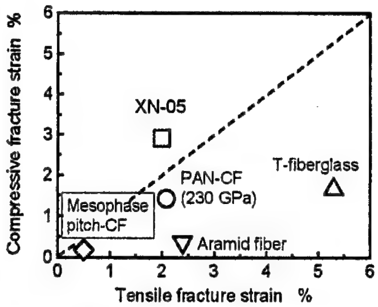
Thermal conductivity of CF from different production lots



Thermal conductivity of CFRP from UD prepreg

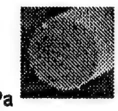
Table Mechanical properties of CF

		Granoc XN-05	PAN-CF E:230GPa	Granoc YS-95A
Fiber properties	Tensile strength MPa	1180	4900	3530
	Tensile modulus GPa	55	230	920
Composite Properties	Compressive strength MPa	870	1400	340
	Compressive modulus GPa	30	130	540



Strain to failure of composites

Granoc XN-05



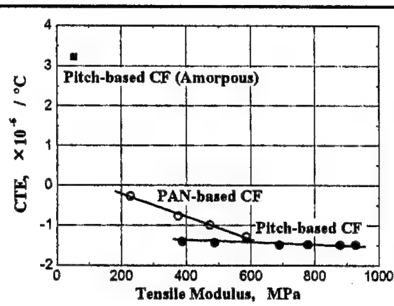
Mechanical properties

1) Continuous low modulus CF with 55 GPa
2) High compressive strain to failure

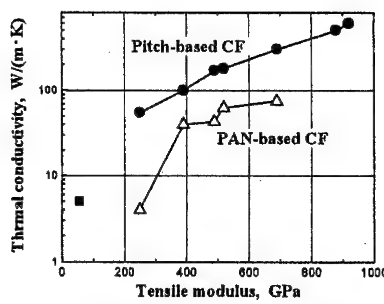
Thermal properties

1) Positive coefficient of thermal expansion
2) Low thermal conductivity

Low density: 1.65 Mg/m³

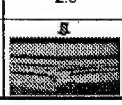
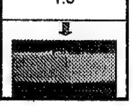


Coefficient of thermal expansion of carbon fibers as a function of modulus



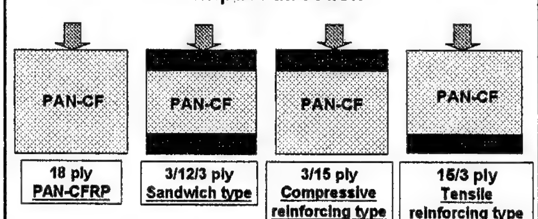
Thermal conductivity of carbon fibers as a function of modulus

Flexural properties of UD-CFRP laminates

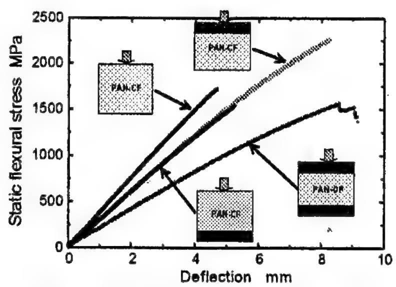
Designation	XN-05 (E: 55 GPa)	PAN-CF (E: 230GPa)
Flexural strength MPa	910	1650
Flexural modulus GPa	30	110
Fracture strain %	2.9	1.5
Fracture mode		

Note) Matrix resin: 130 °C epoxy resin system

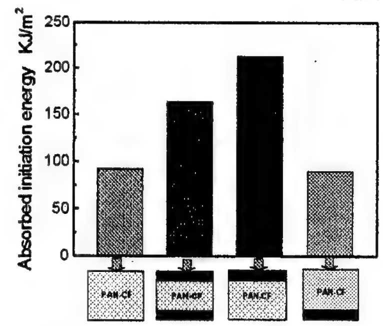
Impact direction



UD-CFRP specimens in impact tests



Stress-deflection curves of UD-CFRP in static tests



Initiation impact energy of UD-CFRP in static flexural tests

Impact mode 1 (flexural load)
3 point bending

	Static	Drop weight	
Velocity m/s	8.3 ×10⁻⁵	5.0	20
Support span mm	60	60	60
Load nose radius mm	5	2	2
Support nose radius mm	2	2	2
Remark			Accelerated with air pressure

Unidirectional laminates
80mm (L) × 10 mm (W) ×2 mm (T)

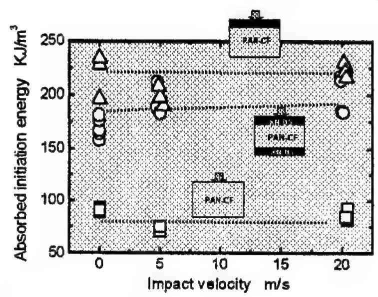


Fig. Dependence of impact properties on impact velocity (CFRP with XN-05)

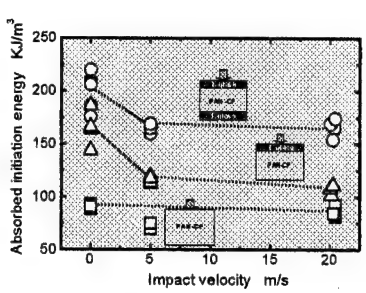
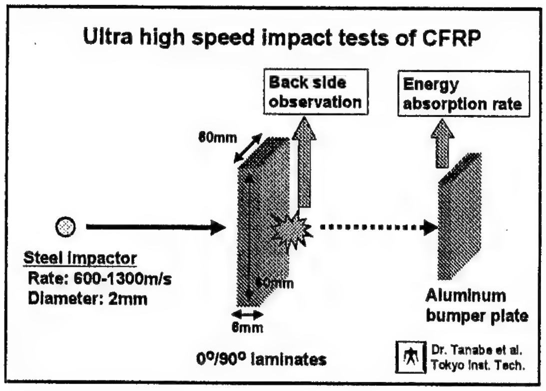


Fig. Dependence of impact properties on impact velocity (CFRP with T-fiberglass)

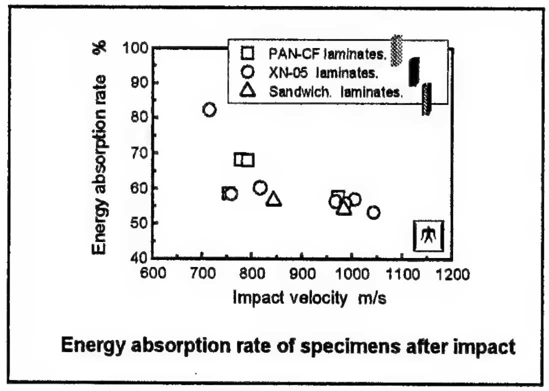
Evaluation of impact properties

Impact mode 2 (ballistic)

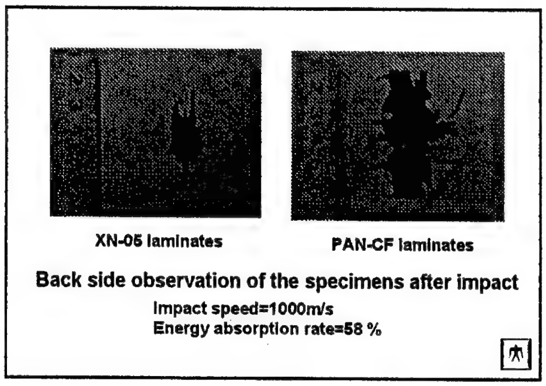
Tests methods	Specimens	
Ultra high speed impact tests 600-1300m/s	0°/90° laminates	Dr. Tanabe at TIT
Compression after impact	QI laminates $[0°/+45°/-45°/90°]_{4S}$	Dr. Ishikawa at NAL



Ultra high speed impact tests of CFRP

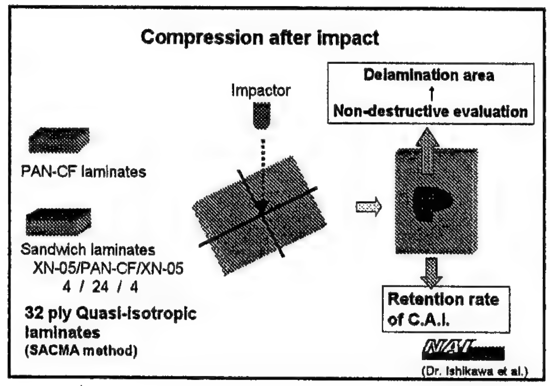


Energy absorption rate of specimens after impact

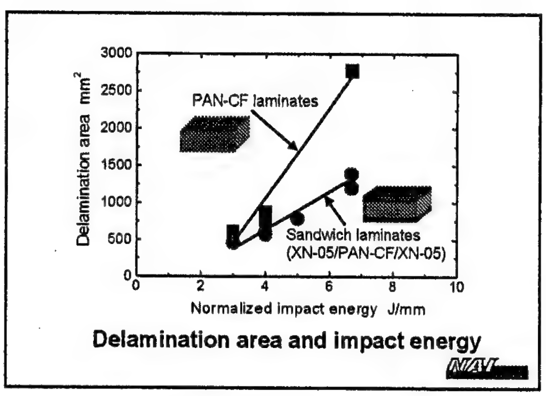


Back side observation of the specimens after impact

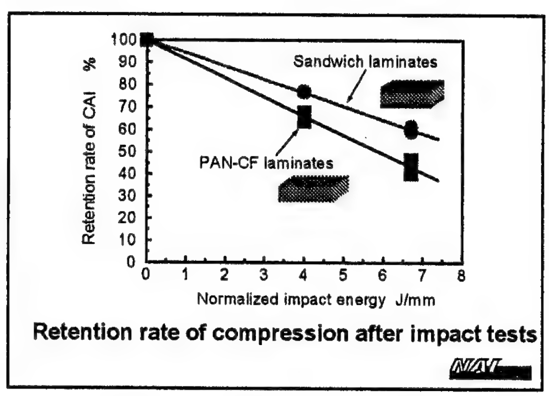
Impact speed=1000m/s
Energy absorption rate=58 %



Compression after impact



Delamination area and impact energy



Retention rate of compression after impact tests

Advanced Composite Materials for Satellite Structures in MELCO

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Advanced Composite Materials for Satellite Structures in MELCO

Tsuyoshi Ozaki
Advanced Technology R & D Center
Mitsubishi Electric Co.

Abstract

Requirements for space satellite structures are lightweight, high strength, and high stiffness not to vibrate sympathetically during launch. Carbon fiber reinforced plastics (CFRP) which have much more strength to weight and stiffness to weight than metals are widely applied to satellite structures and components such as bus structures and solar array panels.

Another feature of this material is its excellent dimensional stability in severe thermal environment. In space, a satellite is put in vacuum and much heat is generated by electrical components, which causes excess heat of the satellite system. In addition, large thermal gradient in the structure may happen due to the exposure to the sun. A satellite has to secure enough pointing accuracy to supply communication, broadcast, and observation services in such severe thermal condition. High thermal stability in dimension of the satellite structures, therefore, is very important as well as heat-resistance. Especially in some special components such as antenna reflectors, application of CFRP whose thermal deformation is much less than metal is essential.

Recently, pitch-based carbon fibers made of petroleum and coal tar pitch have been put to practical use. Some pitch-based carbon fibers have been found to have excellent thermal performance as well as ultra high stiffness. By using the new fibers, we have been developing new composites and applying to satellites.

In the bus structure, we have applied pitch-based CFRP to the earth facing panel. The panel is required to be dimensionally stable and have high thermal conductivity. In addition, aluminum heat pipes should be embedded in order to thermally connect the north and the south panel. Due to the mismatch of thermal expansion between CFRP and aluminum, large thermal stress may causes fracture of the CFRP faceskins. Therefore, we introduced anisotropic laminate design to relieve thermal stress.

Pitch-based CFRP has changed structural design concept of space antenna reflectors. Formerly, antenna reflectors have been made of honeycomb sandwich panels. The CTE of the panels was at best 0.5ppm/K, which caused slight thermal deformation. To restrain such deformation, a rib type structure was introduced as a support structure. When we use pitch-based tri-axial fabric CFRP as a reflector surface, thermal deformation is small enough (<0.2 ppm/K). It requires no support structures to restrain thermal deformation. Therefore we can fabricate space antenna reflectors with a sheet of tri-axial CFRP and thin I-shaped beams to support the reflector.

Another application of the newly developed CFRP is space optics. In the optics, requirements for dimensional stability are much more severe. CFRP pipes for optical structures whose thermal deformation is less than 0.1ppm/K are also to be presented.

CDW'00

COMPOSITES DURABILITY WORKSHOP 2000

Advanced Composite Materials for Satellite Structures in MELCO

Tsuyoshi OZAKI
Advanced Technology R & D Center
Mitsubishi Electric Co.

Requirements for space materials

- Lightweight
- Stiffness
- Strength
- High thermal stability (dimensional)
- High thermal conductivity

Pitch based graphite composite is desirable for

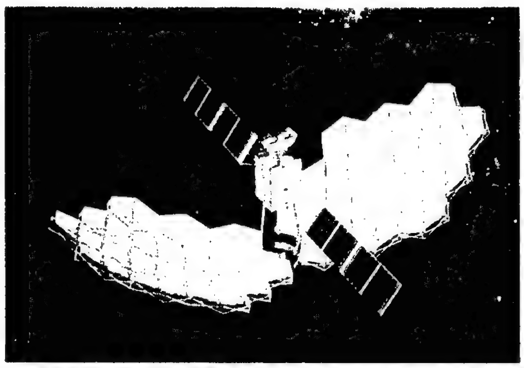
- Structural panel (Heat pipe embedded)
- Antenna reflectors
- Optical sensors

Newly developed bus technologies in ETS-VIII project

(for future high power satellite system)

- Heat pipe embedded earth-facing panel
- Deployable thermal radiator & flexible loop heat pipe system
- Gimbaled ion engines for north-south station keeping

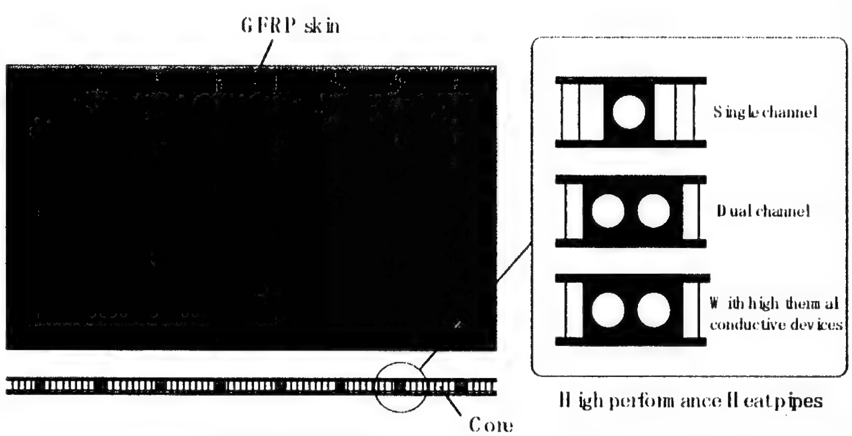
Graphite faceskin heat pipe embedded panel



Graphite faceskin heat pipe embedded panel concept

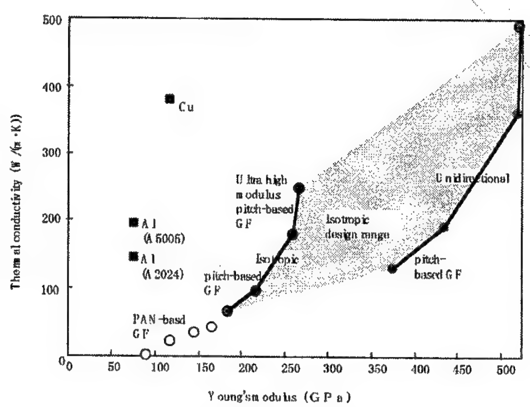
Features of graphite faceskin

- High stiffness with low density
- High thermal conductivity
- Optimal laminate design for mechanical and thermal performance



Advantages of graphite faceskin panels

- Weight saving with high stiffness to weight skins
- Fabrication of thin panel to reduce stowed panel space
- High thermal conductivity for heat transfer



Graphite fibers for faceskins

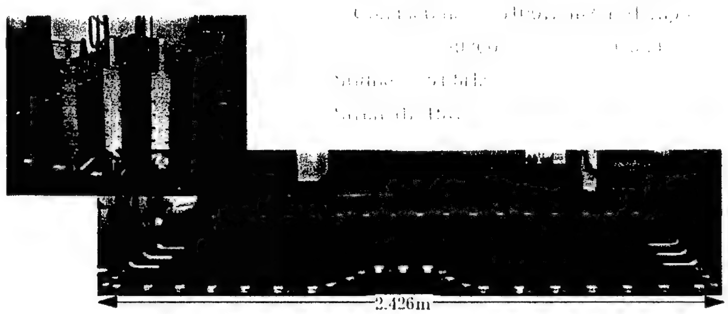
- Pitch-based high modulus fiber, K13C (Mitsubishi Chemical)
- PAN-based high strength fiber, T800 (Toray)

		K13C	T800
Tensile Young's Modulus (GPa)	0°	535	152
	90°	5.0	8.9
Shear Modulus (GPa)		3.9	3.5
Tensile Stress (MPa)	0°	1700	2565
	90°	16.2	66.9
Compressional Strength (MPa)	0°	326	1313
	90°	90	110
CTE (ppm/K)	0°	-1.3	-1.1
	90°	33	30

Thermal stress analysis by non-linear FEM

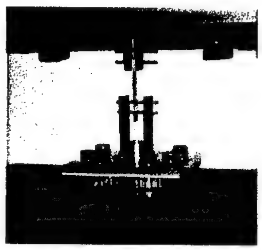
Earth panel for ETS-VIII (Qualification model)

• 2400mmX1200mm

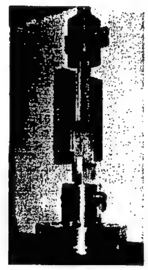


Insert strength of graphite panel (Experimental)

Evaluated both analytically and experimentally ↓



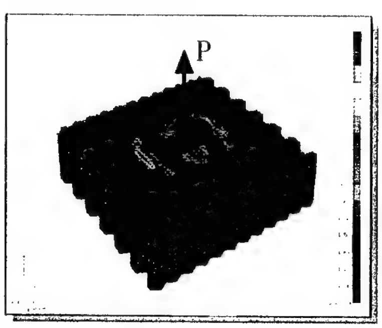
Out of plane : >700N

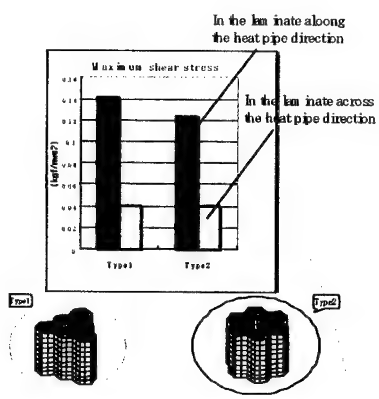


In-plane: >1100N

Insert strength of graphite panel (Analysis)

FEM analysis



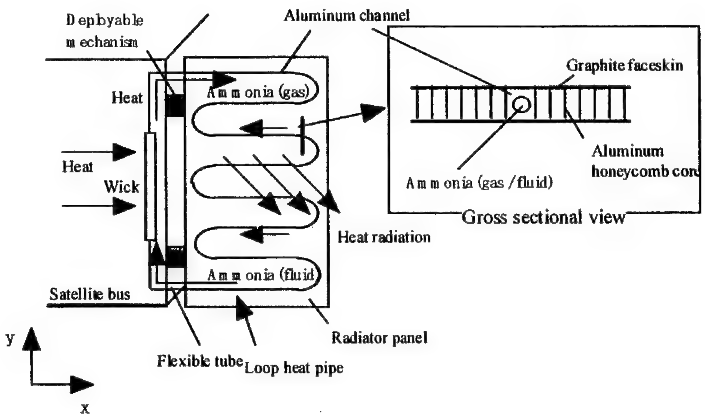


Deployable radiator panel

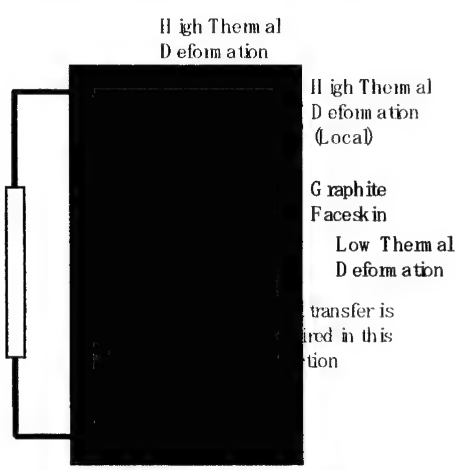
To increase heat rejection capability

Stowed during launch/ Deployed in orbit

to obtain additional heat rejection area



Laminates design of radiator panel



Anisotropic laminate design to

・Relieve significant thermal stress between Al channel and faceskins

・Obtain optimum heat transfer combined with Al channel and faceskins

→Two kinds of graphite materials were applied

Fabrication of full sized panel

- 490mm x 1800mm
- With channel interface
- Cooled down to 188K (No visible damage)

Ultra light weight antenna reflector

Simple structure free from thermal distortion

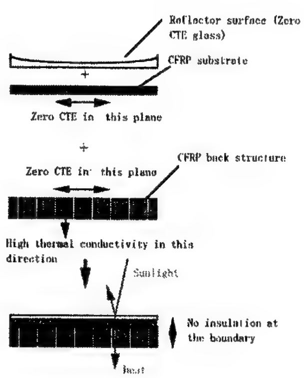
Light weight (13.1→6.2Kg: ϕ 2.6m)

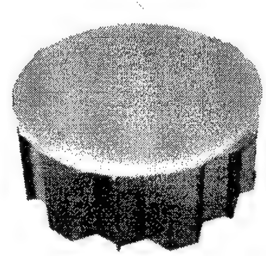
Dual Gridded Antenna Reflector

Small pointinng error
Low electrical loss due to high thermal stability
→Suitable for shaped reflector

Space optical mirror

- High thermal stability (CTE< 0.1 ppm/K)
- Anisotropic composite design to optimize mechanical and thermal demand





Surface error < 16nmRMS
(1/2 Scal model)

Conclusions

Newly developed pitch-based graphite composites have been applied to space satellites such as;

1) Structural panels for thermal management of satellites
2) Deployable radiator panels
3) Antenna reflectors
4) Optical components

Anisotropic laminate design and fabrication techniques have been developed in several projects.

Spacecraft Structures in the Early 21st Century

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Spacecraft Structures In the Early 21st Century

Dr. Steven Huybrechts and Dr Troy Meink

Space Vehicles Directorate
Air Force Research Laboratory
Kirtland AFB, New Mexico USA

Introduction

Space structures will see dramatic changes over the next several decades. These changes are driven not by new materials but by a dramatic shift in the way the world conceives of spacecraft and an expansion in the types of missions being performed from space. Many of these new missions will be military in origin, but the large majority will be commercial as commercial interests take the dominant role in space. The biggest change in spacecraft structures will come about due to a change in the way we conceive of them. The traditional model of one spacecraft bus, launched on an expendable vehicle and supporting one or more payloads, will be superseded through a variety of new architectures including distributed architectures, collaborating constellations, deployable spacecraft, inflatable spacecraft, and reusable vehicles. Additionally, a need for very large apertures in space will lead to a whole class of very large, deployable spacecraft with very strict structural tolerances. Structures will play a key, if not the key, role in making these new space architectures a reality.

The changes to future space architectures can be compartmentalized into two distinct categories: changes to launch systems and changes to spacecraft architectures. These two areas are detailed in the following sections

Future Launch System Structures

Upcoming changes to space structures & materials due to changing launch vehicle architectures can be grouped into three areas:

- **Lower Cost Expendable Launchers:** Expendable launchers will remain the main way to get payloads to orbit. These systems will become increasingly cheaper, particularly due to the introduction of foreign and private systems. The traditional structure development goals of lower cost manufacturing and lighter weight dominate the needs in this area.
- **Reusable Launch Systems:** Despite the dominance of expendable launchers, development of reusable systems must continue if space is to become commonly accessible. The development of an unmanned reusable system is critical to the goal of greatly decreased launch costs. Structural issues commonly found in the aircraft industry, such as durability and operability, dominate the needs in this area. Durable high temperature structure is also of primary importance to this area.
- **Novel Launch Systems:** Several novel launch systems have been proposed in recent years including the use of rail guns, nanoSat launchers on high performance jet fighters, and pulsed lasers. While early in the development phase, these systems have great potential for virtually free launch of the smaller spacecraft concepts. The structures for these systems will need to be able to withstand severe environments, particularly high heat and shock loading, while being very lightweight and stiff.

Future Spacecraft Structures

Upcoming changes to space structures & materials due to changing spacecraft architectures can be grouped into five areas:

- **Maneuvering Space Vehicles:** Maneuvering space vehicles, while challenging from an operational sense, are not as structurally difficult to achieve. Of greatest importance in this area is the need for lightweight hot structure for those vehicles that must be able to re-enter, yet be reusable.
- **Much Smaller Spacecraft (microSats & nanoSats):** Increasingly, microSats (10-100kg) and nanoSats (1-10kg) are becoming highly capable and able to perform large satellite missions. The 'breaking up' of large single satellites into collaborating microSat constellations will become increasingly prevalent as these systems prove to be cheaper, more adaptable, and more defendable. Key structures technologies in this area include structure multifunctionality, producibliity, and intelligence.
- **Much Larger Spacecraft (MonsterSats):** Despite highly capable microSats and nanoSats, future sensing systems will require larger spacecraft due to aperture requirements. The key technology for these systems is the development of very large, highly precise, extremely stiff structures that meet current launch vehicle packaging and weight requirements.
- **High Power Spacecraft:** Modern spacecraft are power starved. For example, a standard GPS spacecraft uses less power than a household hairdryer. For many applications, spacecraft capability is directly related to available power. A host of new technologies, such as thin film photovoltaics and thermal to electric conversion, provide a window of opportunity for structures engineers to redesign the traditional solar cell 'wing' typical to most spacecraft.

Space Structures in the Early 21st Century

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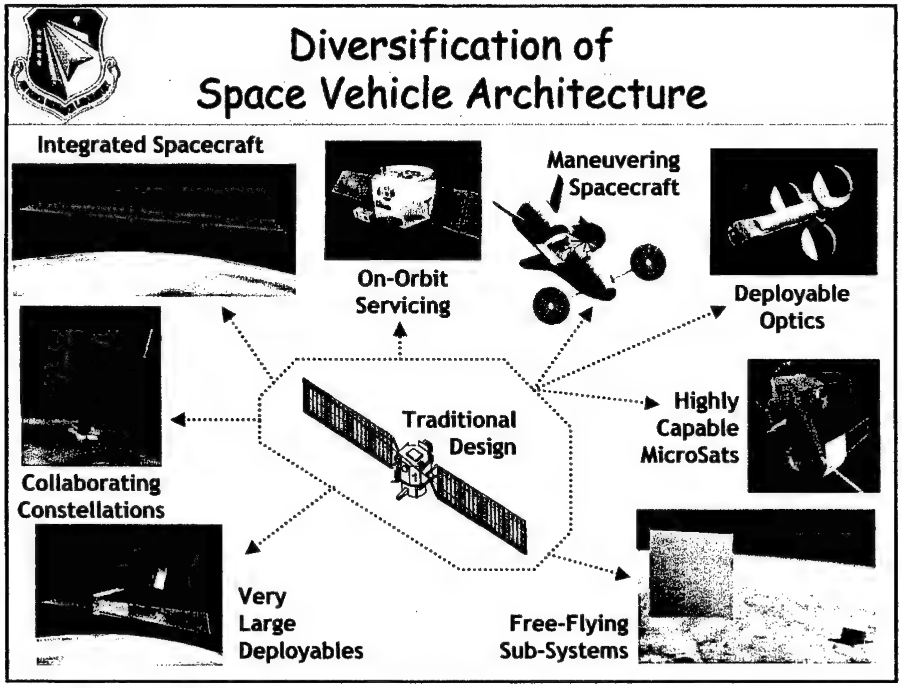
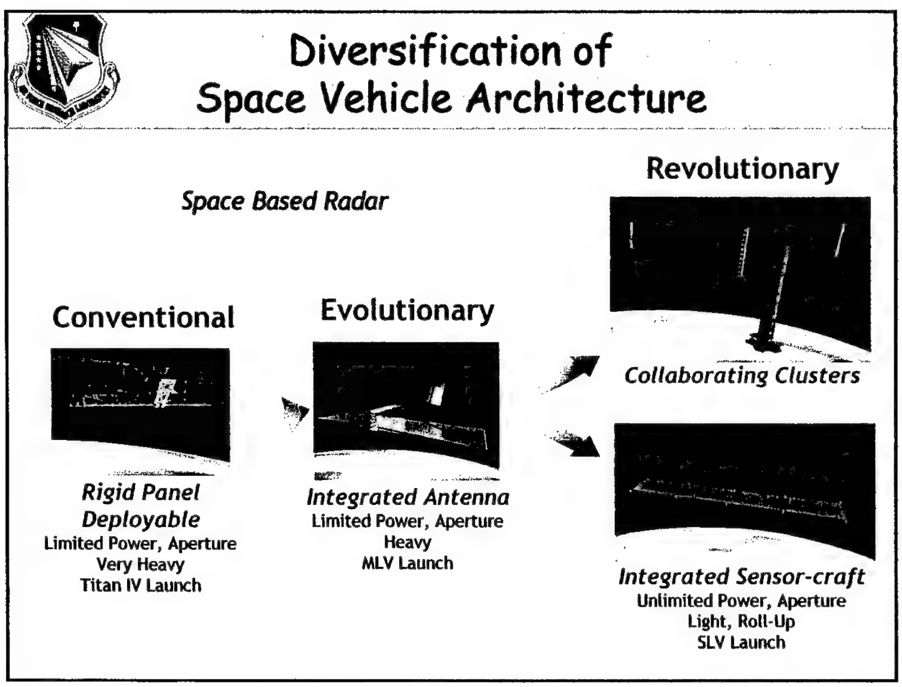
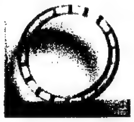
Air Force Research Laboratory

- AF Materiel Command
  - AF Research Laboratory (6400 People, US$1.2 Billion)
    - Air Vehicles
    - Space Vehicles
    - Propulsion
    - Human Effectiveness
    - Directed Energy
    - Information
    - Sensors
    - Materials & Manufacturing
    - Munitions
    - Office of Scientific Research


Diversification of
Space Vehicle Architecture
Integrated Spacecraft
On-Orbit
Servicing
Maneuvering
Spacecraft
Deployable
Optics
Highly
Capable
MicroSats
Traditional
Design
Collaborating
Constellations
Very
Large
Deployables
Free-Flying
Sub-Systems


Diversification of
Space Vehicle Architecture
Space Based Radar
Revolutionary
Conventional
Evolutionary
Collaborating Clusters
Rigid Panel
Deployable
Limited Power, Aperture
Very Heavy
Titan IV Launch
Integrated Antenna
Limited Power, Aperture
Heavy
MLV Launch
Integrated Sensor-craft
Unlimited Power, Aperture
Light, Roll-Up
SLV Launch

Overview



ChamberCore Structures
Durable Composite Structures for Reusable Vehicles

Shape Memory Resin Structures
Deployable Structure for the the PowerSail Concept

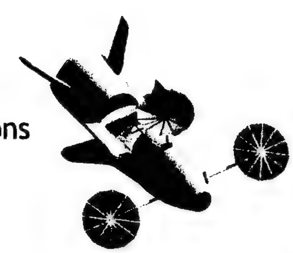
Structures for Deployable Optics
Highly Stiff, Stable Structures for Optical Systems

Future Architecture: Reusable Space Vehicles

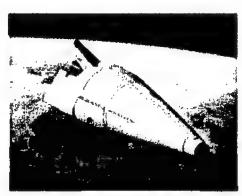
Reusable Launch Systems

Characteristics
Reusable
Routine
Rapid Turnaround Time
"Aircraft-Like" Operations

Key Issues:
Durability
Light Weight



Maneuvering Space Vehicles

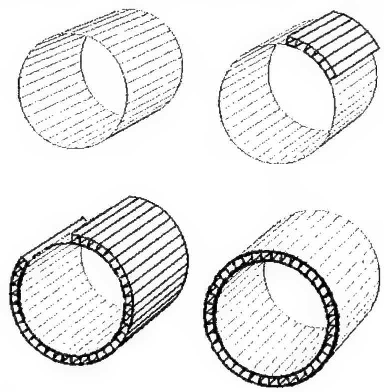


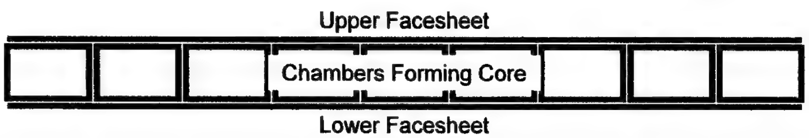
ChamberCore Structures

Very Promising Structure Type For Future Space Vehicles

Integrates:

Very Simple Construction
Low Cost Manufacturing
Flexibility and Configurability
High Structural Efficiency
High Damage Tolerance





ChamberCore Structures

<u>*Acoustics Critical To Acceptance of Composites*</u>

Fairing Acoustic Problem Worsens As Weight Decreases

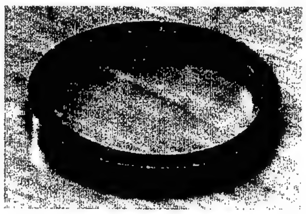
- Boeing (Delta)
  - Delta 2 Composite & Aluminum Fairing Weights Equal, Due to Acoustic Problem
- Boeing (SeaLaunch)
  - Load-Bearing Fairing Structure: 1.07 lb/ft^2
  - Acoustic Treatment: 1.02 lb/ft^2
- Lockheed-Martin (LMLV)
  - Not Interested In Composite Fairings Because of Acoustic Issues

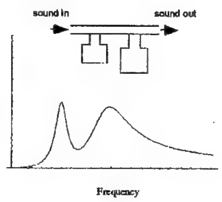
Problem is Extremely Severe in Reusables (X-33, SMV)

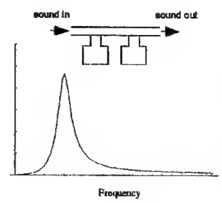
ChamberCore Structures

Integrated Helmholtz Resonators

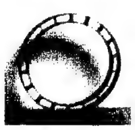
Chambers Can Function as Natural Helmholtz Resonators
5-10 dB Acoustic Noise Reduction With <u>No Weight Penalty</u>







Overview



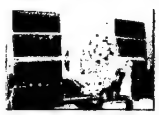
<u>ChamberCore Structures</u>
Durable Composite Structures for Reusable Vehicles

<u>Shape Memory Resin Structures</u>
Deployable Structure for the the PowerSail Concept

<u>Structures for Deployable Optics</u>
Highly Stiff, Stable Structures for Optical Systems

Shape Memory Resin Structures

Today, Most Spacecraft Have Less Power Than A Common Hair Dryer...



GPS Satellite
1000 Watts

Hairdryer
1200 Watts

Future Large Spacecraft Will Require Much Greater Power

Example: Space Based Radar: 25kW - 100kW

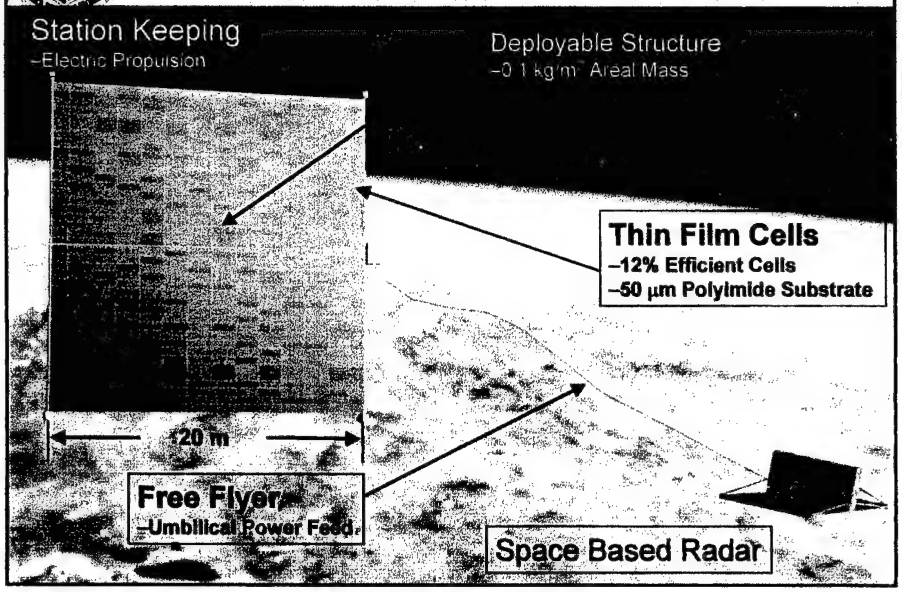
Shape Memory Resin Structures

PowerSail Program

Develop High Performance *Generic* Power System for Next Generation DoD and Commercial Satellites

	Present	PowerSail Demonstration *2005*	PowerSail Operational *2010*
Cost	\$1,000/W	\$300/W	\$200/W
Packaging	8 kW/m³	25 kW/m³	30 kW/m³
Specific Power	85 W/kg	300 W/kg	600 W/kg
Available Power	15 kW	50 kW	100 kW

Shape Memory Resin Structures



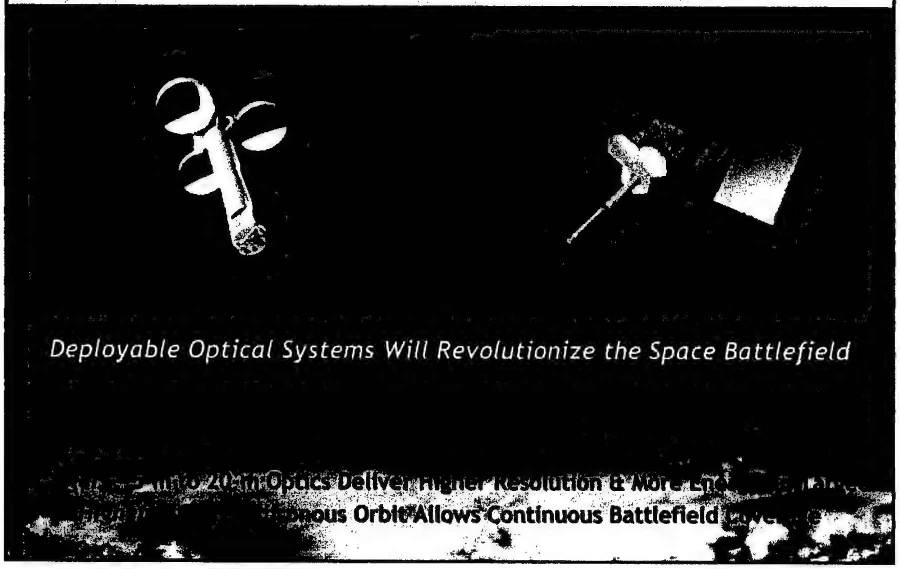
Overview

ChamberCore Structures
Durable Composite Structures for Reusable Vehicles

Shape Memory Resin Structures
Deployable Structure for the the PowerSail Concept

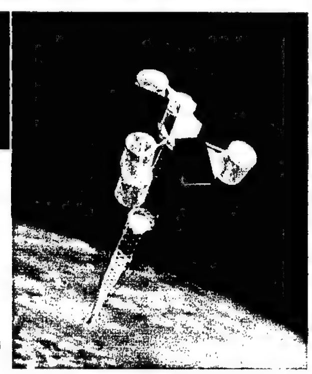
Structures for Deployable Optics
Highly Stiff, Stable Structures for Optical Systems

Deployable Optics



Major Challenges of Deployable Optical Systems

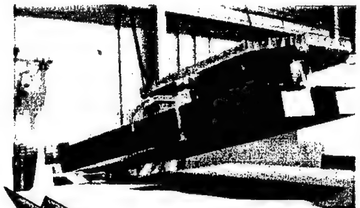
Driver is Deployable Tolerance Requirement
~10 nm Accuracy



- Highly Advanced Actuators
  - Very High Precision
  - While Retaining Large Stroke
- Extremely Stiff Structure
  - Well Characterized
  - Precision
- Predictable Repeatable Deployment
  - Minimize MicroLurch, Creep
- Ultra-Lightweight Mirrors
- Highly Advanced Non-Linear Control Solution
- Adaptive optics

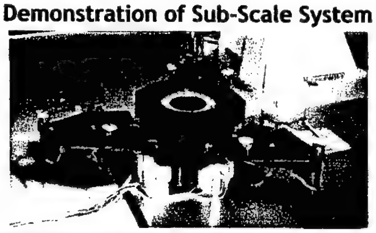
UltraLITE Deployable Optics Program

1996
Concept Drawings & Feasibility Studies



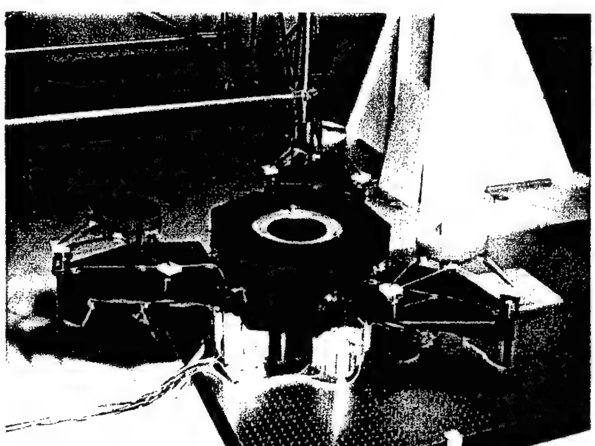
1997-1998
Full-Scale Deployable Single Petal Demonstrated 20 nm Piston Control

1999-2000
Demonstration of Sub-Scale System

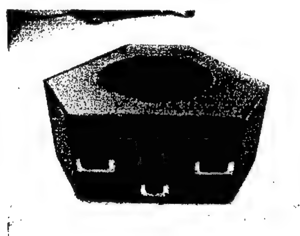


2003?
Hubble-Sized Optics Launched in Taurus Fairing

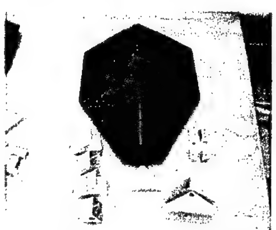
UltraLITE Deployable Optics Program

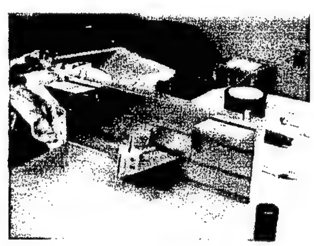


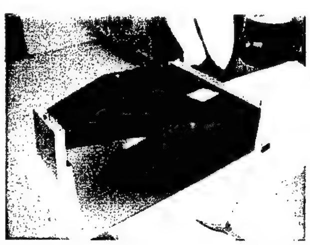
UltraLITE Deployable Optics Program

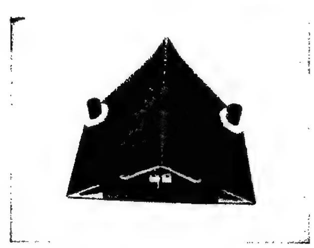


UltraLITE Deployable Optics Program

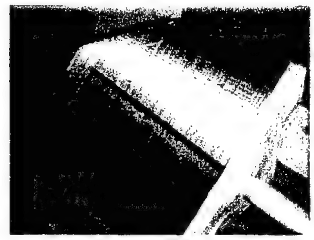


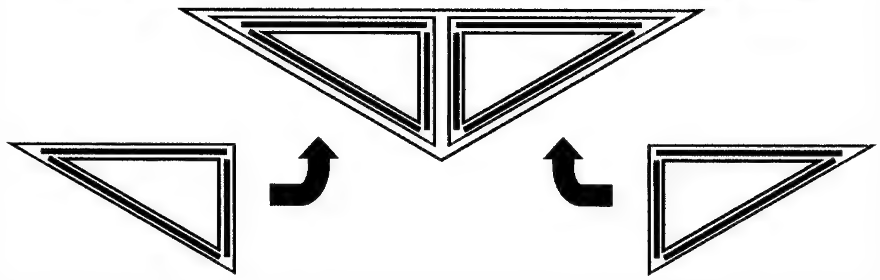






UltraLITE Deployable Optics Program





Summary

Past:
Focus on Payloads

Future:
Focus on Spacecraft Technologies
Leading to Radical New Architectures

On the Tensile Strength of Carbon Fiber-Unsaturated Polyester Resin Strand Specimens

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Zenichiro Maekawa

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On the tensile strength of carbon fiber – unsaturated polyester resin strand specimens

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CFRP is a useful material to reduce the energy consumption of automobiles, rapid trains, machinery, etc, and to substantiate long span bridges such as a suspension bridge across the Strait of Gibraltar, very tall buildings, very deep off shore oil rigs, etc. In order to achieve this task low cost and reliability are unavoidable conditions.

Epoxy resin has been used dominantly as the matrix of composite materials since BFRP and CFRP developed in 1960s to 1970s. Unsaturated polyester and vinyl ester resin has been used also for boats, ships, yachts, and other marine application by empirical knowledge with GFRP. According to tradition the epoxy composites perform better than the unsaturated polyester or vinyl ester composites as for mechanical properties; it is presumed that the difference is attributable to poor resin-to-fiber bonding and brittleness of the cured resin. On thermoplastic resins PEEK, PEI, PPS, etc have been evaluated and good to fair tensile strength of composite materials were reported, but PE, PP, ABS, and other cheap resins are not well studied.

In this experiment tensile strength of CFRP made of the said three thermoset resins is tested. Test specimen is 3000 filaments single end strand which is impregnated with the resin then cured fully. Since unsaturated polyester and vinyl ester resin contain about 40% of styrene and evaporation of styrene can cause the strength of the cured resin, carbon fiber strand is impregnated, squeezed, and sandwiched with two narrow PP tapes then wound up on a square frame.

Carbon fiber		Toray Industries	TORAYCA T300B-3000-40B
Unsaturated polyester	1A	Mitsui Chemicals	ESTER P825
	1B	Takeda Chemicals	POLYMAR 6339
	1C	Dainihon Ink	POLYLITE FW231C
Vinyl ester	2D	Nippon Shokubai	EPOLAC RF701
	2E	Showa Highpolymer	RIPOXY R802
	2F	Japan U.PICA	NEOPOL 8411L
		Hardener	MEKPO/Co Naphthenate

Epoxy	3G	Shell Chemicals	EPIKOTE827/DICY/DCMU/PVF
	3H	Union Carbide	BAKELITE ERL4221/BF3MEA
Cure conditions	UP & VE : RT(10C~25C)*12h~24h + 60C~80C*1~2h + 100C*3h		
	Epoxy : 3G: 120C*2h	3H: 125C*1h	
Fiber content	40~55% by mass		

As shown in Figure 1 to Figure 3, it is evident that the distribution of tensile loads at failure for eight samples with three different resin types is same. This is encouraging result and hence effect of fiber content, multiplication of the number of strands and its configuration, thermoplastic resin matrix, etc will be studied in terms of cost and reliability on the tensile strength of CFRP .

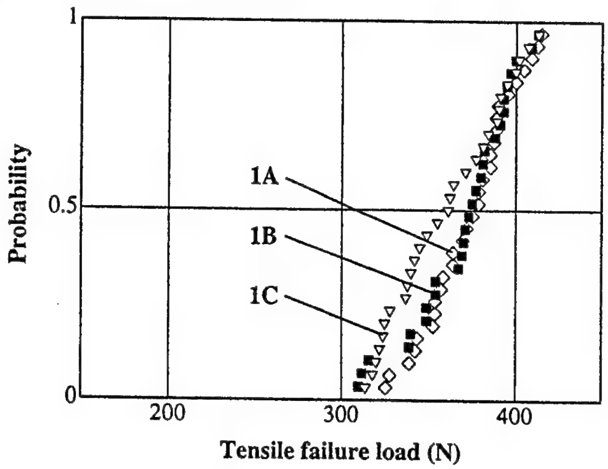


Figure 1 Unsaturated polyester resin

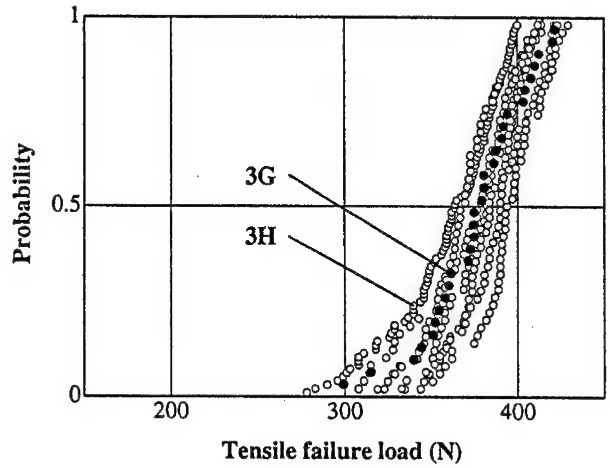


Figure 3 Epoxy resin

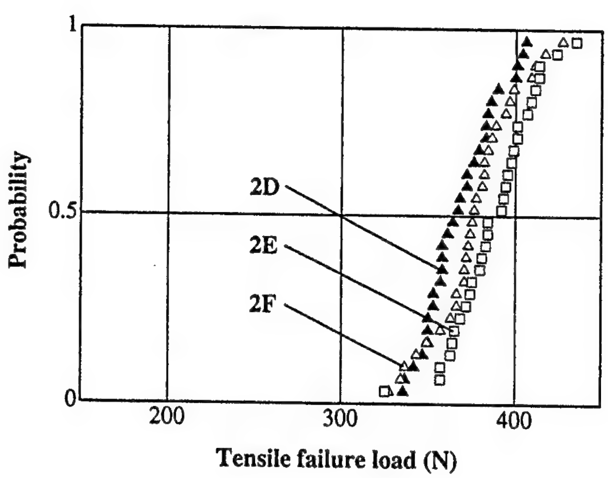


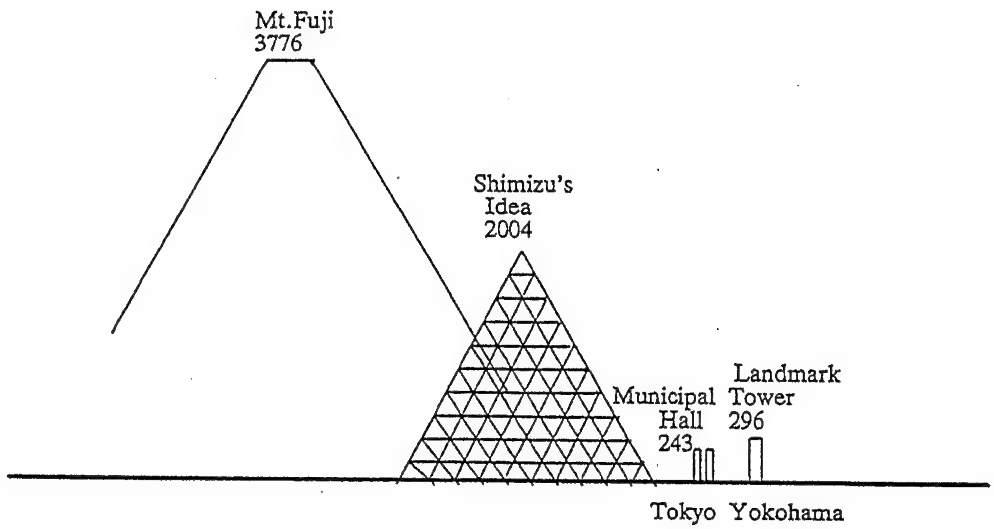
Figure 2 Vinylester resin

On the Tensile Strength of

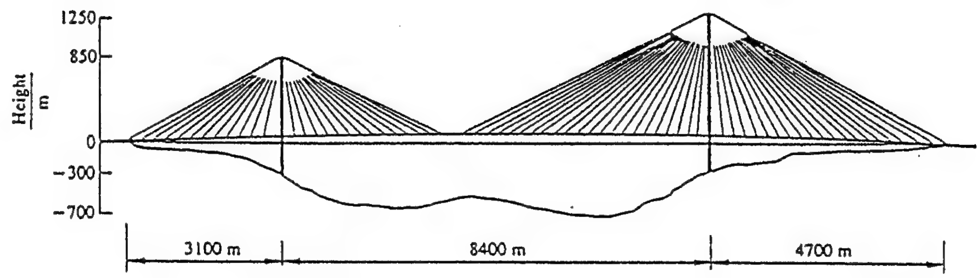
Carbon Fiber – Unsaturated Polyester Resin Strand Specimens

Junichi Matsui, VentureLabo

Zenichiro Maekawa, Kyoto Institute of Technology



Plan for a Very Tall CFRP Building by Shimizu Co. in Japan (1991)



Plan for a CFRP Bridge across the Strait of Gibraltar by Meier in Swiss(1986)

CFRP Strand Specimens with Different Resins

1:Unsaturated Polyester Resin	1A:Mitsui Chemicals	ESTER P825
	1B:Takeda Chemical	POLYMAR 6339
	1C:Dainihon Ink	POLYLITE FW231C
2: Vinylester Resin	2D:Nippon Shokubai	EPOLAC RF701
	2E:Showa Highpolymer	RIPOXY R802
	2F:Japan U.PICA	NEOPOL 8411
3: Epoxy Resin	3G:Shell	EPIKOTE827/CICY/DCMU
	3H:UCC	BAKELITE ERL4221/BF3MEA

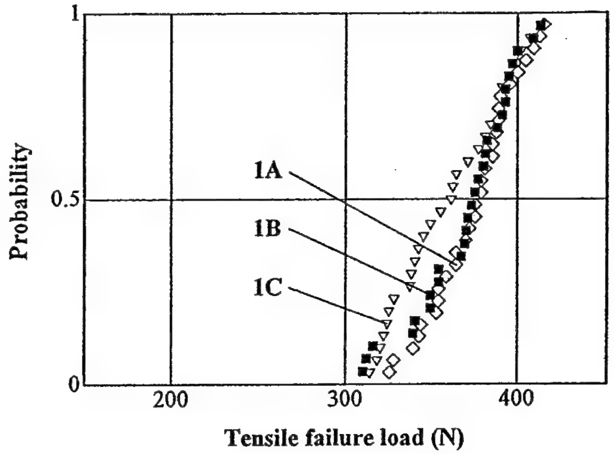


Figure 1 Unsaturated polyester resin

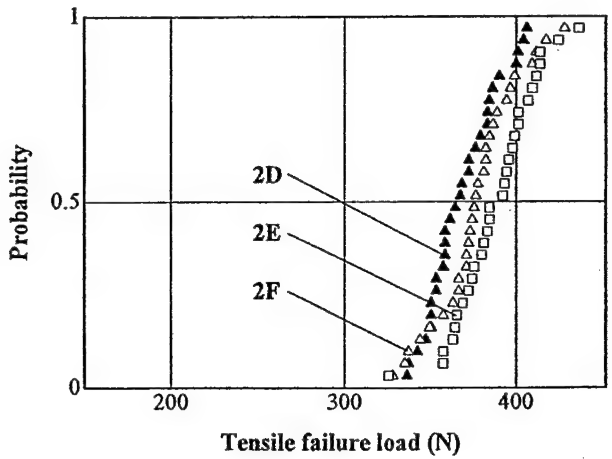


Figure 2 Vinylester resin

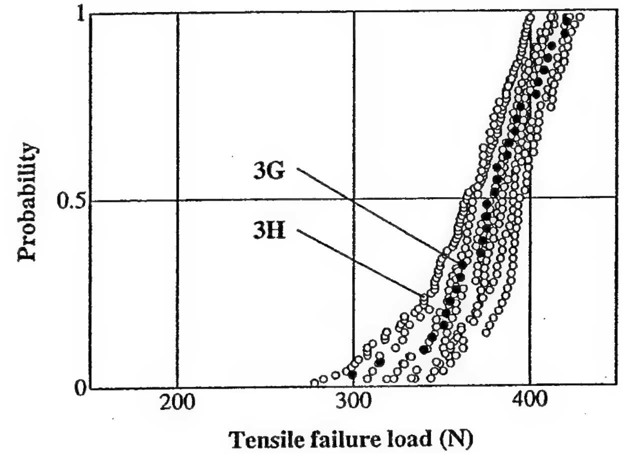


Figure 3 Epoxy resin

Tensile Failure Load of CFRP Strand Specimens with Different Resins

Specimen	Tensile failure load Average (N)	Standard deviation (N)	Coefficient of Variation (%)
1A	374	23.9	6.4
1B	370	27.4	7.4
1C	360	30.1	8.4
2D	368	19.7	5.3
2E	387	22.8	5.9
2F	376	23.4	6.2
3G	376	28.5	7.6
3H	360	30.8	8.6

Modeling Post-Buckled Delaminations in Composites

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Modeling Post-Buckled Delaminations in Composites

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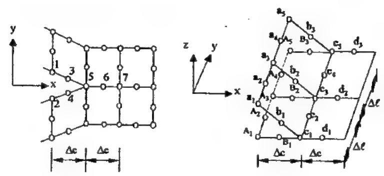
Abstract:

This paper deals with the computational modeling of delamination and the prediction of delamination growth in laminated composites. In the analysis of post-buckled delaminations, an important parameter is the distribution of the local strain energy release rate along the delamination front. A study using virtual crack closure technique is made for three-dimensional finite element models of circular delaminations embedded in woven and non-woven composite laminates. The delamination is embedded at different depths along the thickness direction of the laminates. The issue of symmetry boundary conditions is discussed. It is found that fibre orientation of the plies in the delaminated part play an important role in the distribution of the local strain energy release rate. This implies that the popular use of quarter models in order to save computational effort is unjustified and will lead to erroneous results. Comparison is made with experimental results and growth of the delamination front with fatigue cycling is predicted. A methodology for the prediction of delamination areas and directions using evolution criteria derived from test coupon data is also described. It is found that evolution criteria based on components of the strain energy release rate predict the rate of delamination growth much better than evolution criteria based on the total strain energy release rate.

Keywords: Delamination, Finite element analysis, Strain energy release rate, Fatigue, Modeling.

Use of FE enables computation of local strain energy release rates (SERR) by the virtual crack closure technique (VCCT) along the delamination front.

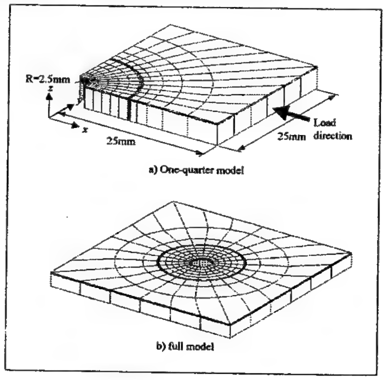


Questions:

- Reduce computational effort and cost:
  - 2D analysis (plane strain or axisymmetric) ?
  - Quasi 3D analysis (plate or shell elements) ?
  - Effect of boundary conditions (St Venant's Principle) ?
- Are local SERRs useful for predicting direction and magnitude of growth ?
  - Comparison with experimental data. Growth criteria.
- Model contact of delamination surfaces ?
- Mesh-dependency ?

3D FE analysis and experimental program.

- Quasi-isotropic lay-up $[(0/45/-45/90)_3]_S$
- Centrally located hole of diameter 5 mm.
- Circular delamination (Teflon insert) of diameter 20 mm.
- Peak compressive fatigue load of 30 kN (R = -1).

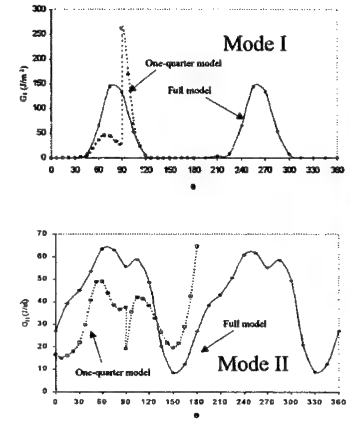


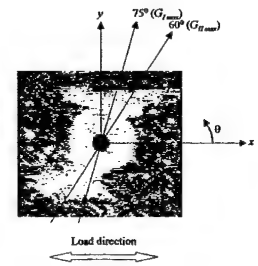
a) One-quarter model

b) full model

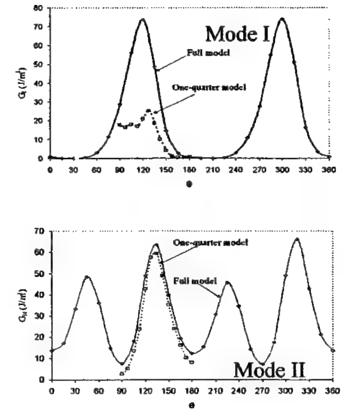
One-Quarter FE Models	Full FE Models	Experiment Specimens	Position of Delamination	Ply Angles adjacent to Delamination.	Sublaminate Lay-up
Q1	F1	E1	Between layers 1 & 2	0/45	[0]
Q2	F2	E2	Between layers 2 & 3	45/-45	[0/45]
Q3	F3	E3	Between layers 3 & 4	-45/90	[0/45/-45]
Q4	F4	E4	Between layers 4 & 5	90/0	[0/45/-45/90]

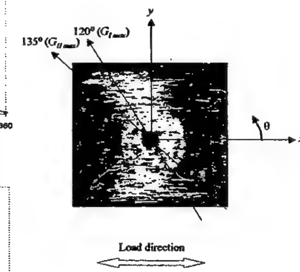
Sublaminate [0/45]



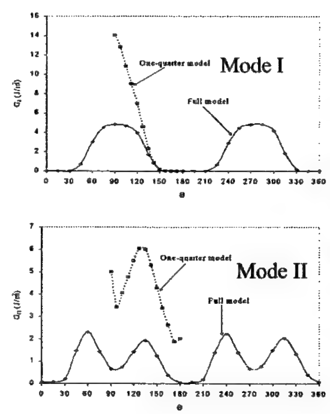


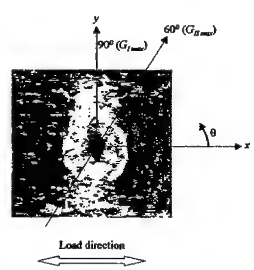
Sublaminate [0/45/-45]



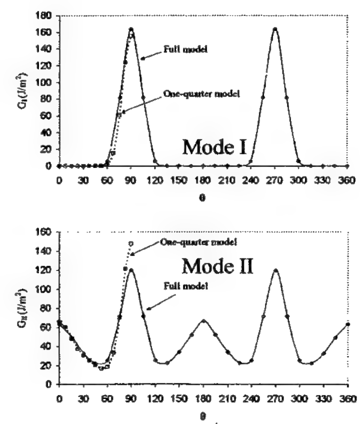


Sublaminate [0/45/-45/90]





Sublaminate [0]



No experimental data available because of extensive transverse matrix cracking in sublaminate.

Quantitative evaluation of delamination growth.

Simpler to consider woven fabric composite plates.

Propagation criteria:

1. Based on total SERR: $\frac{dA}{dN} = 3014 \cdot \left(\frac{\Delta G_T}{1000}\right)^{7.43}$

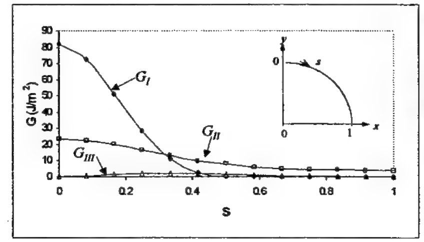
   Mohlin, T., Blom, A.F., Carlsson, L.A. and Gustavsson, A.I., "Delamination Growth in a Notched Graphite/Epoxy Laminate under Compression Fatigue Loading", *Delamination and Debonding of Materials*, ASTM STP 876, W.S. Johnson, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp.168-188

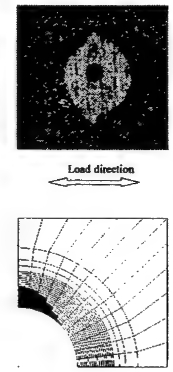
2. Based on SERR components:

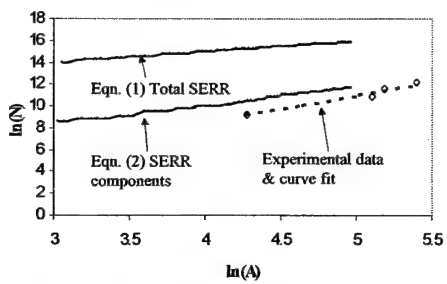
$$\frac{dA}{dN} = 0.7188 \cdot \left(\frac{G_{I\max}}{103}\right)^{8} + 6.5938 \cdot \left(\frac{G_{II\max}}{456}\right)^{6}$$

Ramkumar, R.L. and Whitcomb, J.D., "Characterization of Mode I and Mixed-Mode Delamination Growth in T300/5208 Graphite/Epoxy", *Delamination and Debonding of Materials*, ASTM STP 876, W.S. Johnson, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp.168-188.

Numerical iterative procedure based on a local cumulative damage coefficient.







Propagation criterion based on SERR components appear to agree better with experimental data.

Conclusion

➢ Direction of maximum growth generally coincides with direction of maximum strain energy release rate (SERR).

➢ Boundary conditions and sublaminate lay-up significantly affect distribution of local SERR. One-quarter models should be avoided.

➢ A method for predicting delamination growth is proposed. Propagation criteria employing SERR components (rather than total SERR) show closer agreement to experimental data.

Characterization of Damage Progression in Multidirectional Symmetric FRP Laminates

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CDW '00, August 23, 2000, Tokyo, Japan

CHARACTERIZATION OF DAMAGE PROGRESSION IN MULTIDIRECTIONAL SYMMETRIC FRP LAMINATES

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It is well known that two kinds of damage, namely intralaminar (transverse) cracking and interlaminar delamination occur at a fairly early stage well before the ultimate failure in case of tensile loading of multidirectional symmetric FRP laminates [1]. This damage progression often results in some reduction in stiffness and is also likely to influence the ultimate failure strength. Therefore the prediction of such an early damage progression in laminated composite members is very important from the viewpoint of "Damage Tolerance Design (DTD)" of composite structures. As the initial damage such as intralaminar cracking is generally observed to progress in a stable manner, it is possible to set the allowable stress level at a higher value than the conventional "First Ply Failure (FPF)" level, if the damage progression mechanism is thoroughly understood. This would give us a theoretical basis for establishing a more advanced "Predictable Damage Growth Design (PDGD)" methodology for composite structures resulting in a further significant weight reduction .

To clarify the damage mechanisms of laminates, a large number of damage models have been proposed and various analytical and experimental characterizations on damage progression have been performed mostly for relatively simple laminated structures such as cross-ply laminates [2] but very few for general-purpose multidirectional laminated composites such as quasi-isotropic laminates. For this reason, this paper aims at proposing a general method to predict intralaminar crack density of each ply and stress-strain relation under multi-axial inplane tensile loading for multidirectional laminates. The method is based on an energy approach equating the released energy by transverse crack growth to the decrease in potential energy stored in a laminate [3]. Both can be estimated from the stiffness reduction of laminates due to intralaminar crack growth, which is obtained by numerical calculation of the stress and strain field in a damaged zone. The influence of ply thickness and stacking sequence on the damage behavior is analyzed by numerical simulations.

Acoustic emission characteristics and internal damage progression of multidirectioanl CFRP symmetric laminates are investigated experimentally by applying tensile tests of coupon specimens which are composed of 0-, 45- and 90-degree layers. The initiation of intralaminar crack in 90- and 45-degree layers and the onset of edge delamination in the interlainar region are monitored by acoustic emission. The internal cracks are observed by micrography and the interlaminar delamination is detected by using ultrasonic C-scan technique. Predicted damage state of quasi-isotropic laminates and stress-strain equation are compared with the experimental results. Predicted stress of crack initiation by the proposed theory agrees well with critical stress observed by acoustic emission. It is shown that the intralaminar cracking damage behavior of multidirectional symmetric laminates is predictable by the proposed method and the prediction generally agrees well with the simulated results in terms of crack initiation and crack density.

This work has been carried out and still continuing as a part of fundamental research on the damage tolerance design of composite structures in the 5-year project on advanced composite materials for transportation starting from 1998 in R & D Institute of Metals and Composites for Future Industries (RIMCOF) sponsored by the Ministry of International Trade and Industry. It is shown that the proposed prediction method is successful as far as intralaminar crack is concerned. However the actual more complicated damage mode should have to be modeled by including interlaminar delamination and extension of crack to the adjacent layer which requires a further extension and modification of the proposed method.

References

[1] T. K. O'Brien , et al.: Tensile Fatigue Analysis and Life Prediction for Composite Laminates, NASA TM 100549, 88-B-015 (1998).

[2] I. Ohsawa, I. Kimpara, et al.: Acoustical Analysis of Transverse Lamina Cracking in CFRP Laminates, Proc. 4th Intern. Sympos. On Acoustic Emission from Composite Materials (AECM-4) (1992), 55-64.

[3] K. Tohgo, et al.: Ply Cracking Damage Theory and Damage Behavior in CFRP Cross-ply Laminates, Proc. A of JSME, 64, No. 621 (1998), 30-37 (in Japanese).

CHARACTERIZATION OF DAMAGE PROGRESSION IN MULTIDIRECTIONAL SYMMETRIC FRP LAMINATES

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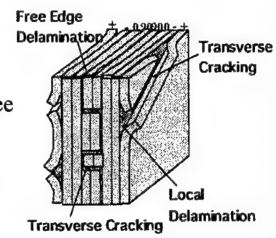
The University of Tokyo

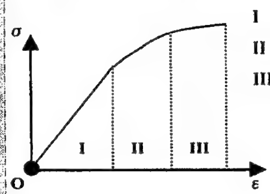
Failure Modes in Composite Laminates

- Intralamina (Transverse) Cracking
- Interlaminar (Free Edge/Local) Delamination
- Fiber Breakage



Damage Progression in Composite Laminates

- Stress-Strain Relation



I Elastic Range
II Intralaminar Cracking
III Intralaminar Cracking
Interlaminar Delamination
Fiber Breakage

Damage in Composite Structures

- Intralaminar Cracking
  - ・・・Thermal Residual Stresses
  - ・・・Secondary Machining
  - ・・・Loading
- Tolerance of Stable Growth Damage
- Importance of Initial *Intralaminar Cracking*

Problems in Damage Prediction

- Damage in Multidirectional Laminates depends on Laminate Constitution (Ply thickness, Ply angle)
- Many Parameters, Difficulty in Modeling
  - Mostly on Cross Ply Laminates (Togoh, McCartney)
  - Very Few on Quasi-Isotropic Laminates (Shahid)

Present Design Criteria

- Based on Stress Criterion of Failure
  - The Effects of Ply Thickness and Stacking Sequence is not considered
- Even Stable Growth Damage is Intolerable
  - Difficulty in Damage Modeling

Limited Allowable Stress Level
(Conservative Design)

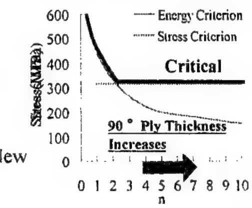
1

Motivation of Research

- Prediction of Initial Damage Progression Behavior in General Multidirectioanl Laminates
- Failure Criterion Considering Ply Thickness and Stacking Sequence
- Predictable Damage Growth Design (PDGD) Methodology

Failure Criterion

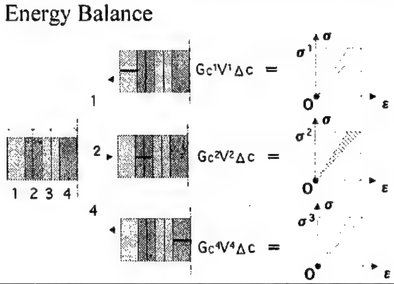
- Stress Criterion
  - Failure at Critical Stress of a Certain Level
- Energy Criterion
  - Failure at Critical Energy to form a New Fracture Surface



$[0_n/90_{2n}]$s Laminate

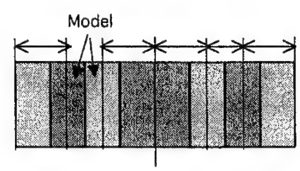
Damage Prediction based on Energy Release Rate

- Energy Balance



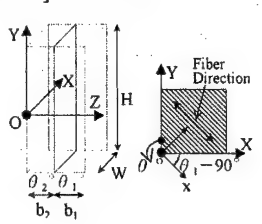
Modeling of Laminate

- Divided at Center of Ply Thickness
  - • • • Inplane Stress Continuity
  - • • • Simple Symmetric Laminate Elements



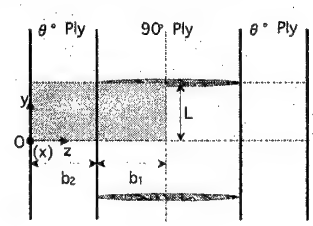
Divided Elements of Laminate

- Coordinate Transformation from $[\theta_1/\theta_2]$s to $[\theta/90]$s Element



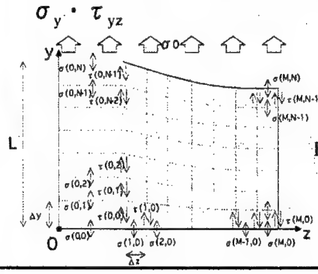
Stiffness Reduction in Laminate

- Rigidity of $[\theta/90]$s Element



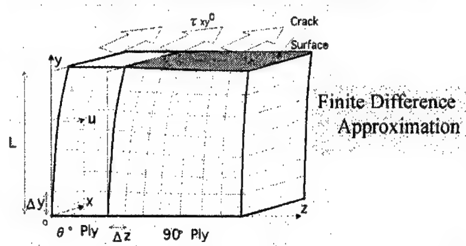
Reduction in Tensile Rigidity

- Discretization of Stress Distribution



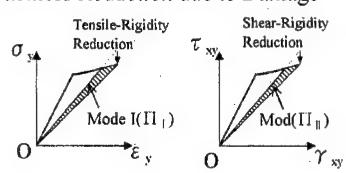
Reduction in Shear Rigidity

- Discretization of x-direction Displacement



Stress-Strain Relation

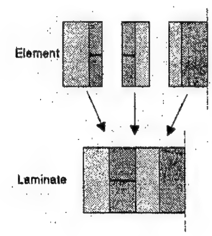
- Stiffness Reduction due to Damage



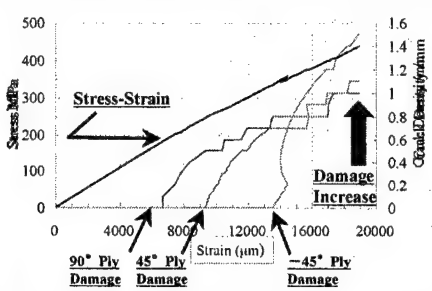
$$\frac{G_I}{G_{II}} = \frac{\Pi_I}{\Pi_{II}}$$

Assembly of Elements

- Superposition of Elements
  - Lamination Theory
- Damaged Layer
  - Averaging of Divided Elements

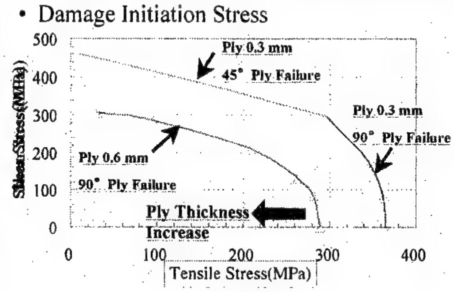


Example of Analysis ---(1)
$[45_4/0_1/-45_4/90_4]$s Laminate



Example of Analysis ---(2)
Effect of Ply Thickness

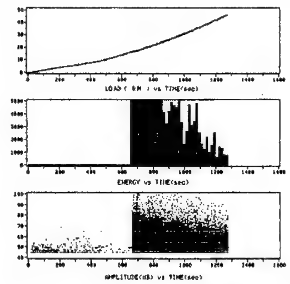
- Damage Initiation Stress



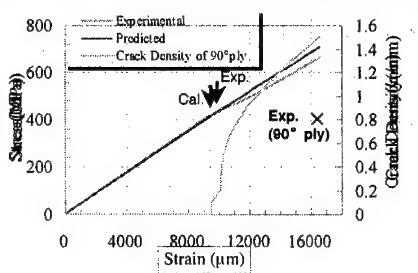
Laminate Constitution of Test Specimens

Constitution	Ply Number	90° Ply
$[45_2/\text{-}45_2/0_2/90_2]s$	16	0.3mm
$[45_4/\text{-}45_4/0_4/90_4]s$	32	0.6mm
$[45_2/0_2/\text{-}45_2/90_2]s$	16	0.3mm
$[45_4/0_4/\text{-}45_4/90_4]s$	32	0.6mm
$[45_2/\text{-}45_2/0_1/90_2]s$	14	0.3mm
$[45_4/\text{-}45_4/0_1/90_4]s$	26	0.6mm
$[45_2/0_1/\text{-}45_2/90_2]s$	14	0.3mm
$[45_4/0_1/\text{-}45_4/90_4]s$	26	0.6mm

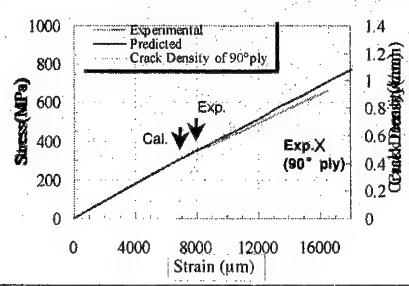
Diagram of AE Output of $[45_4/\text{-}45_4/0_4/90_4]$ s Laminates.



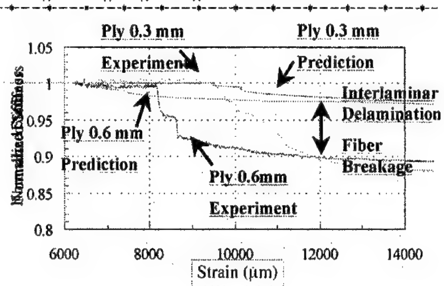
$[45_2/\text{-}45_2/0_2/90_2]s$ (Ply 0.3mm)



$[45_4/\text{-}45_4/0_4/90_4]s$ (Ply 0.6mm)



Stiffness Reduction in $[45_n/\text{-}45_n/0_n/90_n]s$ Laminate



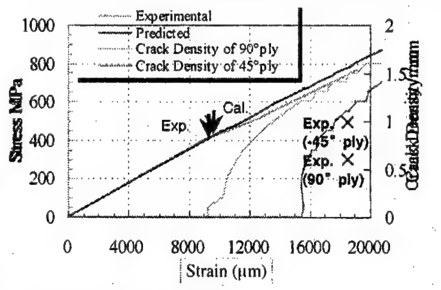
Summary of $[45_n/\text{-}45_n/0_n/90_n]s$

- Effect of Ply Thickness
  - Good Agreement between Prediction and Experiment for Damage Initiation Stress
- Damage Density
  - Predicted Damage Density does not agree well with Edge Observation after Unloading
- Stiffness Reduction
  - Effects of Interlaminar Delamination and Fiber Breakage have to be considered

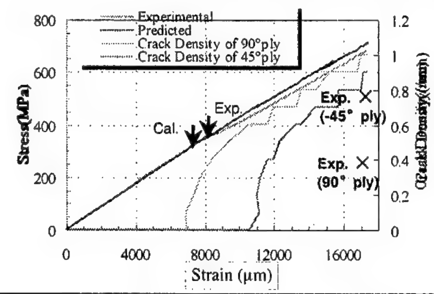
Note : Similar Tendency in $[45_n/\text{-}45_n/0_1/90_n]s$

4

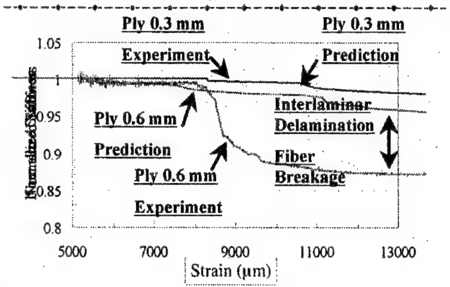
$[45_2/0_2/-45_2/90_2]$s (Ply 0.3mm)



$[45_4/0_4/-45_4/90_4]$s (Ply 0.6mm)



Stiffness Reduction in $[45_n/0_n/-45_n/90_n]$s Laminate



Summary of $[45_n/0_n/-45_n/90_n]$s

- Effect of Ply Thickness
  - Good Agreement between Preiction and Experiment for Different Stacking Sequence
- Mutual Interaction of Cracks
  - Interaction Effect of Cracks has to be considered in Stacking Sequence where Crack Extends to Adjacent Layer

Note : Similar Tendency in $[45_n/0_1/-45_n/90_n]$s

Conclusions

- Intralaminar Cracking Damage Behavior of Multidirectional Symmetric Laminates is shown to be predictable by the Proposed Method
- Prediction and Experiment agree well for Damage Initiation Stress

Future Problems

- More Sophisticated Modeling Comsidering Interlaminar Delamination and Fiber Breakage
- Formulation of Mutual Interaction Effect of Cracks
- Continuous Damage Detection by Experiment

An Information System for Composites Durability

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An Information System for Composites Durability

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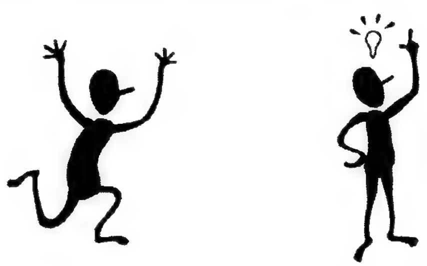
UCLA

Presented at the CDW 00
Aug. 23, 2000, Tokyo, Japan

1

Purpose of Presentation

- Not to show past achievements
- But to discuss future directions



2

Outline

- New Technologies
- Why Information Systems?
- Database Development
- Durability Database
- Discussion and Conclusions

3

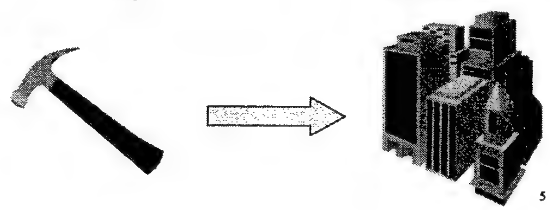
New Technologies

- Information Technology
- Nanotechnology
- Biotechnology
- Smart Materials and Structures

4

Information Revolution

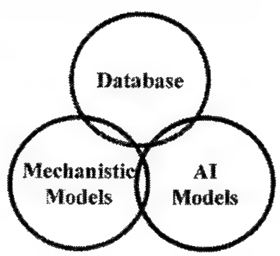
- 1st Revolution: Printing machines
- 2nd Revolution: Computers
- Lessons Learned
  - Paradigm shift from tools to contents



5

Information System

- A software package that provides the information we need.
- Consists of a database, mechanistic models and artificial intelligence models (expert systems, neural networks, genetic algorithms, etc.)



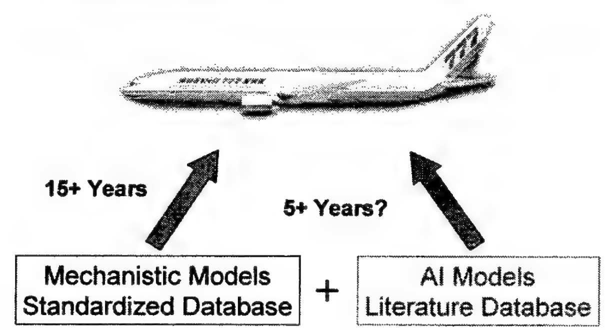
6

Why Information Systems?

- Accelerated Insertion of Materials
- Independent development of design allowables time consuming and costly
- Test standardization difficult to achieve
- Efficient use of literature data
- Validation of models and test results

7

Utilization of New Materials



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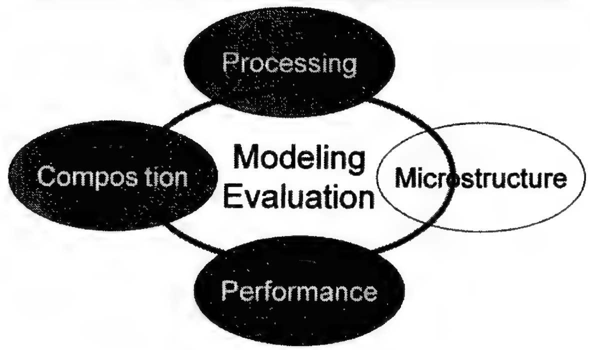
Material Development



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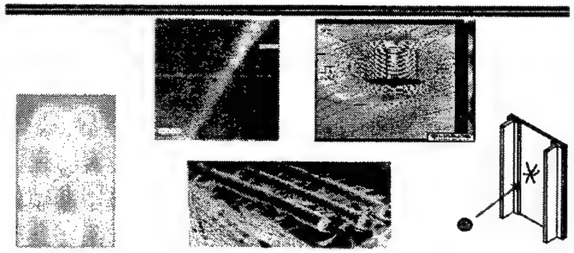
Mechanistic Models



10^{-12} m	10^{-9} m	10^{-6} m	10^{-3} m	10^{0} m
Quantum Mechanics	Nano-Mechanics	Micro-Mechanics	Meso-Mechanics	Macro-Mechanics

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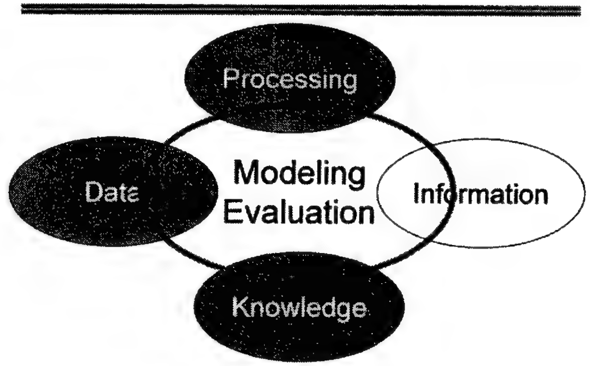
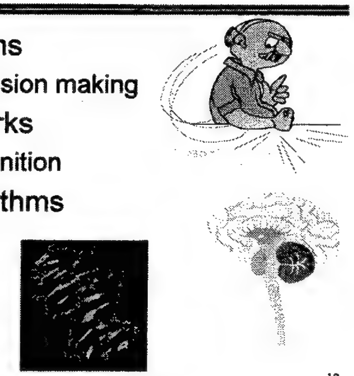
Knowledge Development



10

Artificial Intelligence Models

- Expert Systems
  - Heuristic decision making
- Neural Networks
  - Pattern recognition
- Genetic Algorithms
  - Optimization



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Database Development

- Database
  - A collection of information
  - Easy and efficient to store information
  - Easy to retrieve, analyze and display information
- Microsoft Access
  - Relational database
- Visual Basic
  - User interface

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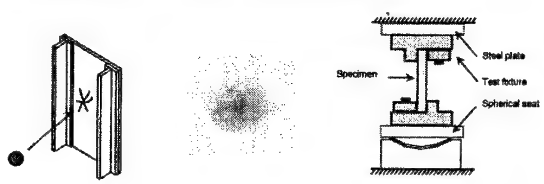
Damage Tolerance

- Resistance to incidence of damage and tolerance to presence of damage
- Limited to impact damage



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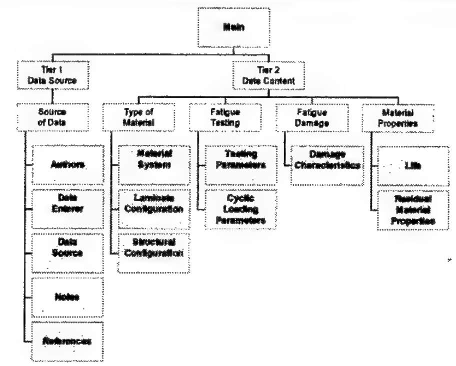
Database Structure



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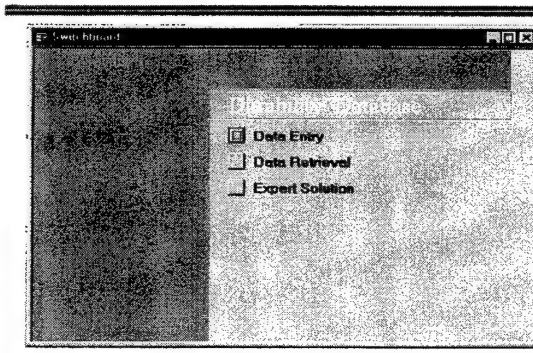
Data Entry



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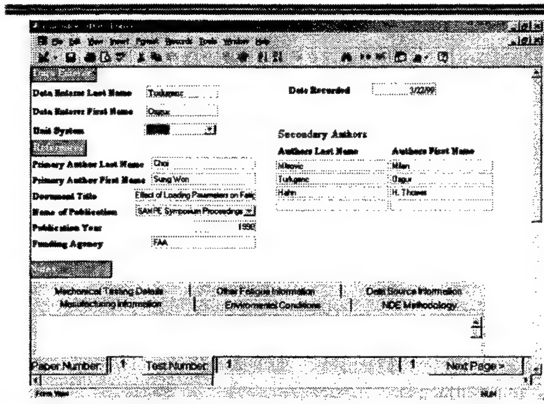
Source of Data



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Stored Data - I

- All fatigue related data from the FAA project phases II, III, IV, and V
- Plain specimens
  - Ply crack density, life
  - T-T, T-C, C-C, block
- Impacted specimens
  - Two energy levels
  - Damage diameter, life
  - C-C, block, full and modified TWIST spectrum
- Open-hole specimens
  - Split length, life
  - T-T, T-C, C-C, full and modified TWIST spectrum

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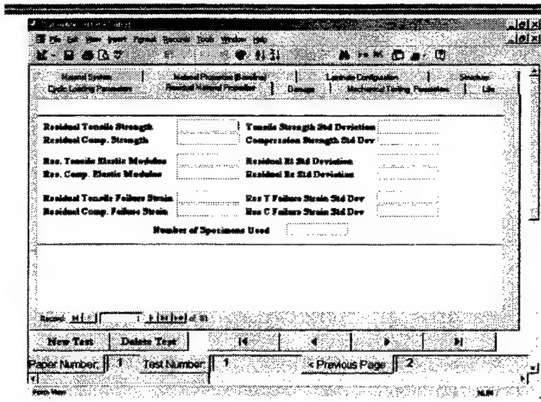
Property Data



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Stored Data - II

- Ryder (1980)
  - Residual properties, life
  - T-T, T-C, C-C
- Spearing and Beaumont (1992)
  - split length growth from center notch
  - T-T
- Rotem (1993)
  - Life
  - T-C, several frequencies
- Komorowski et al. (1995)
  - Life
  - T-C

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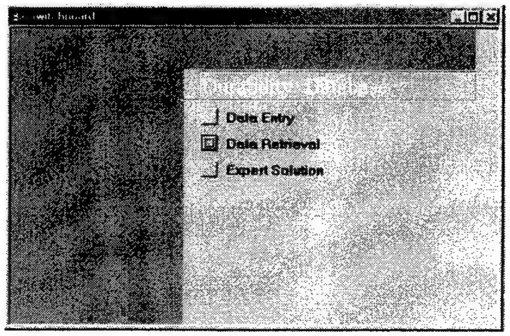
Data Retrieval



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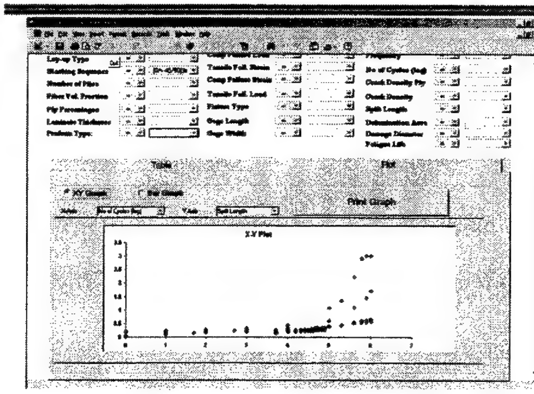
Solution Output



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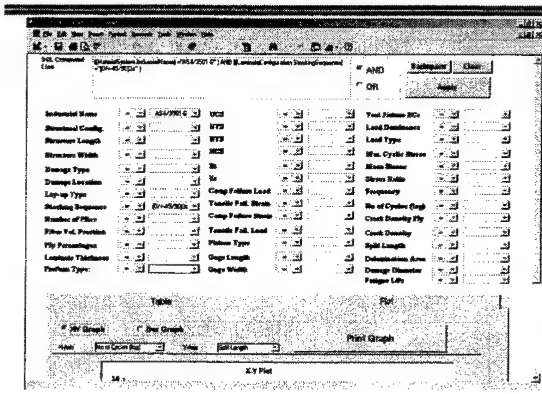
Question Input



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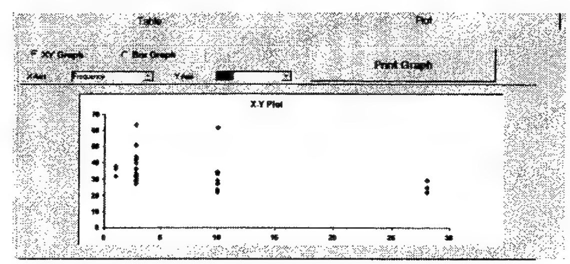
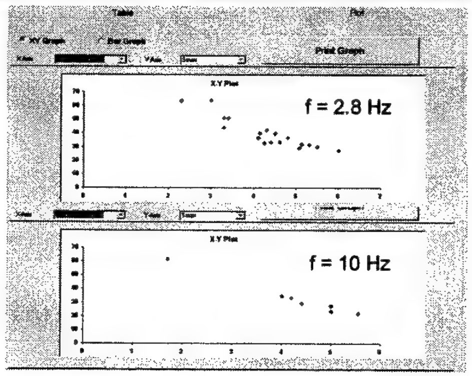
Frequency Effect

- Stored data
  - T300/934 quasi-isotropic 16-ply laminate
  - Data at R=-1 and f = 1, 2.8, 10, 28 Hz



Frequency Effect (cont'd)



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Material/Lay-Up Effect

- Stored data
  - AS4/3501-6, IM6/5245C
  - $[\pm 45/0_2/90/0_2/\text{-}{+45}]_S$, $[90/(0/45)_2/(-45/0)_2]_S$
  - R = -3.75

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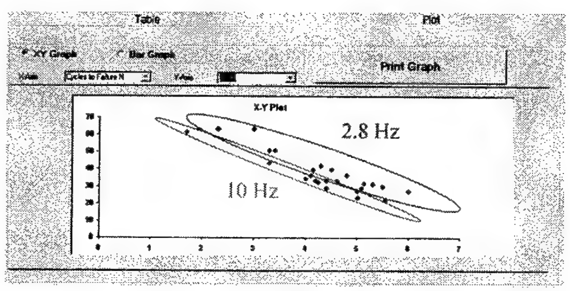
Frequency Effect (cont'd)



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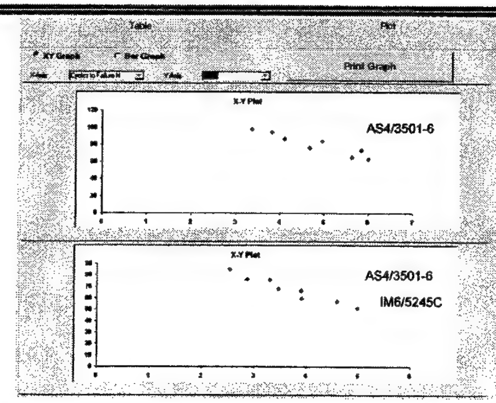
Material Effect



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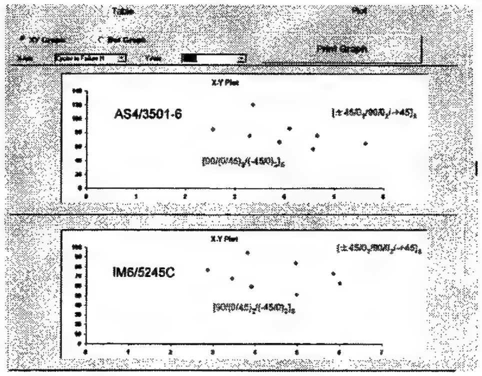
Lay-Up Effect



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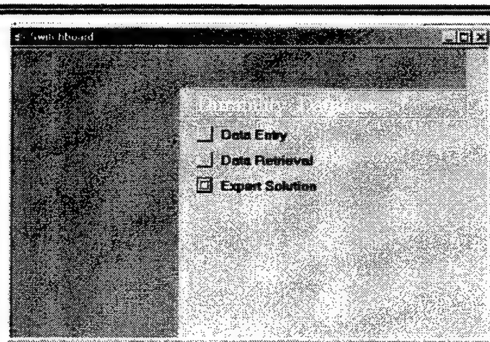
Expert Solution



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Method

- No data available for desired conditions
- Input
  - Choose an average value and range for each parameter (i) of interest
  - Assign a weight (W_i) to indicate relative importance
  - Assign a confidence level (C_i)
- Output
  - RTS, RCS
  - Split length, delamination area, damage diameter
  - Overall Confidence (C_{Total})

$$C_{Total} = \frac{\sum_{i=1}^{N} W_i \times C_i \times B_i}{\sum_{i=1}^{N} W_i}$$

B_i : Boolean Operator

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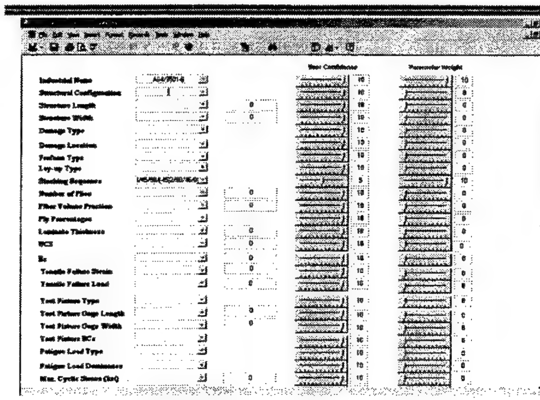
Requirement Input



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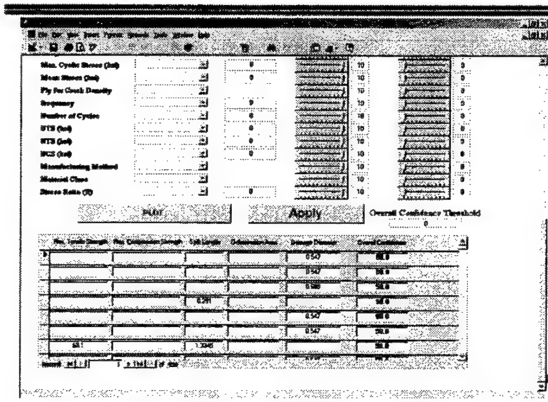
Solution Output



Discussion & Conclusions

- Extensive amount of data available to be input: collaboration needed
- Better format for data input
- AI models to be developed
  - Expert systems
  - Neural networks
  - Genetic algorithms
- First step toward an information system for composites durability

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Development of Space Frame and Monocoque Panel with CFRP for Large-Span Structures

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Development of Space Frame and Monocoque Panel with CFRP For Large-span Structures

Kenichi SUGIZAKI, Institute of Technology, SHIMIZU Corporation, Tokyo, Japan

ABSTACT

We are engaged in the development and application of large-span structural systems for the twenty-first century using a new material, CFRP. In this report, I will outline the Double-Layer Space Frame and the Monocoque Panel using CFRP (Carbon Fiber Reinforced Plastics) as a structural material.

CFRP is lighter than Steel that is most common structural material. And it has superior specific strength (material strength /specific gravity) as well as specific rigidity (Young's modulus /specific gravity). Therefore, we believe that we can construct lighter roof buildings using CFRP than Steel and the others.

In Japan, seismic load make structural properties heavy influence. If roof structures of buildings are lighter than usual ones, seismic load of the buildings are commonly decreased. So, we believe that the durability of buildings will become increased.

Structures with CFRP perform well from the point of view of strength, specific stiffness, heat insulation, corrosion resistance, etc. I will focus on the durability of buildings using the Truss system and Monocoque Panel with CFRP.

Development of Space Frame and Monocoque Panel With CFRP For Large-span Structures

< The Realization of the new created space using new materials >

2000. 08. 23
Kenichi SUGIZAKI
Shimizu Corporation

The realization of the new created space using new materials | *Introduction*

< CFRP has excelent characteristics for structure material. >
< CFRP products perform well from the point of view of strength, specific stiffness, >
< heat insulation, corrosion resistance, etc. >

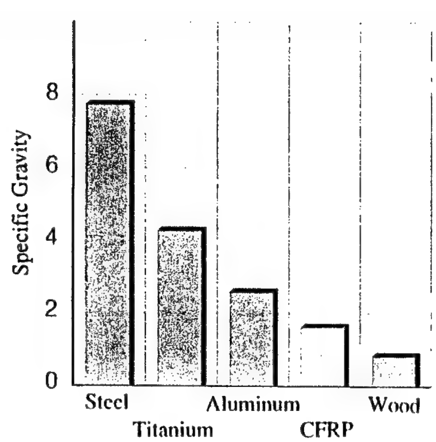


Fig. 1 Specific Gravity of Common Structure Materials

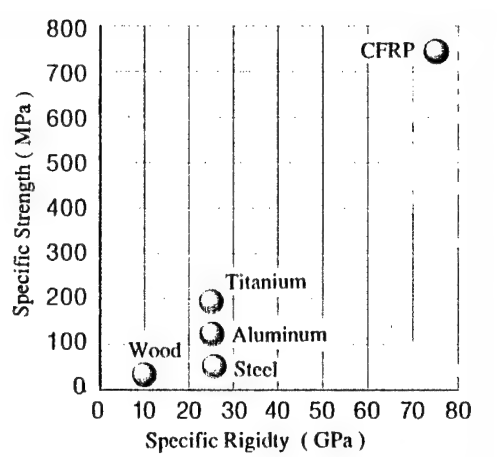


Fig. 2 Specific Strength and Specific Rigidity of Common Structure Materials

The realization of the new created space using new materials | Concept

< A free form / The light space / Long life life-space >
< The space changes with the new material, CFRP. >

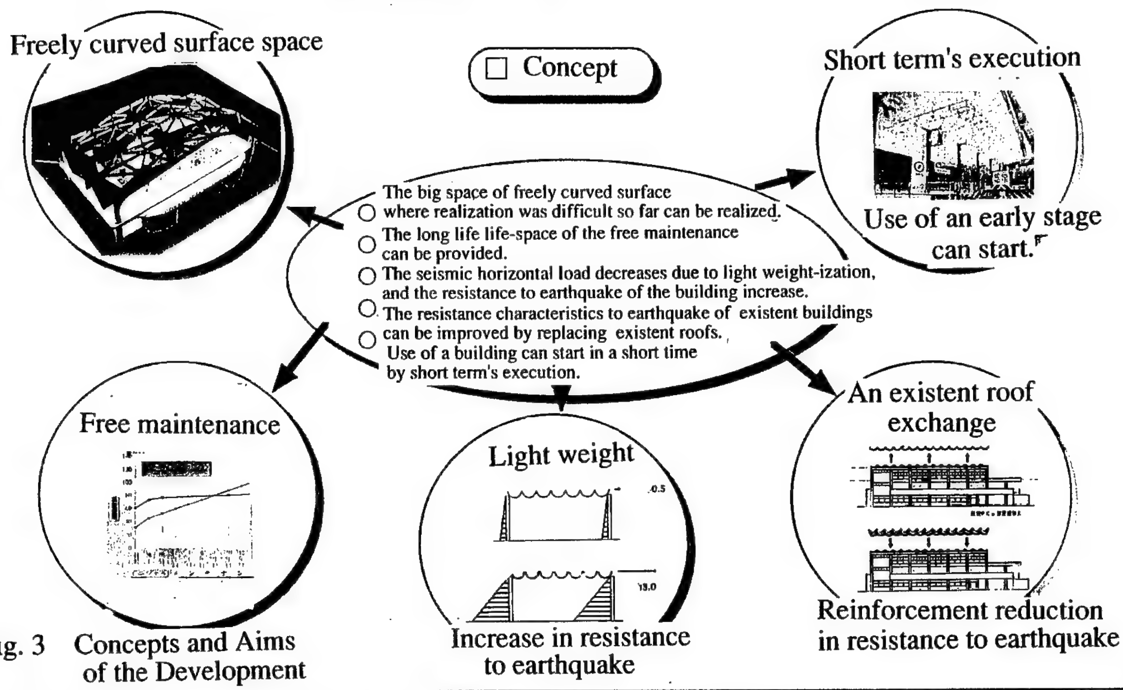


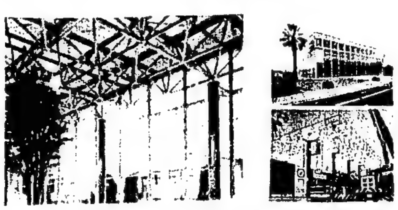
Fig. 3 Concepts and Aims of the Development

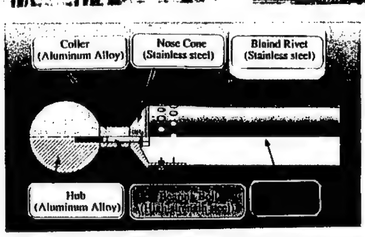
The realization of the new created space using new materials | Outline of the Structural Systems with CFRP

< Line-up of the Realization technologies. >
< The line-up of the new structure space where new material was used is completed, >
< and the most suitable structure space is provided. >

CFRP Double-layer Space Frame

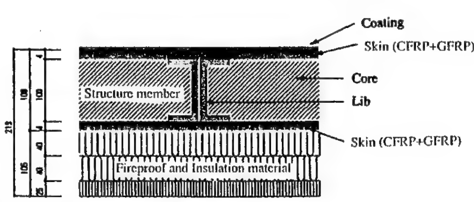
- ○ Double-layer Space Frame composed of CFRP pipes
- ○ Because members are light weight, assembled easily, and short term's execution is easy.





CFRP Monocoque Panel Roof

- ○ The freely curved surface Shell structure using the CFRP Monocoque Panels
- ○ Large curved surface structure can be made in the construction place.



The CFRP Space Frame | General Technologies

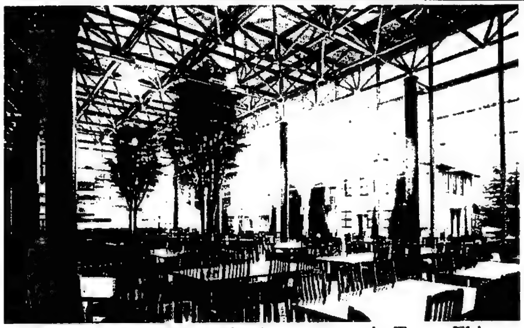


Photo 1 Internal view of the refreshment room in Toray-Ehime

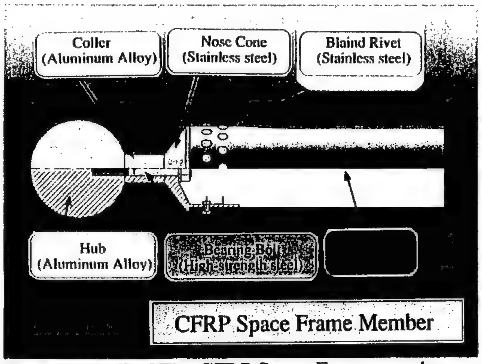
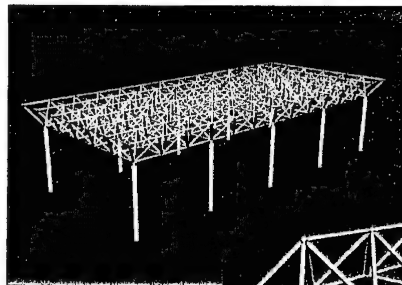


Fig. 4 Detail of The CFRP Space Frame member



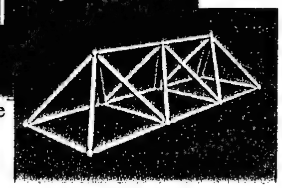


Fig. 5 Structural Image of Flat Roof

Fig. 6 Units of CFRP Space Frame

Design form example

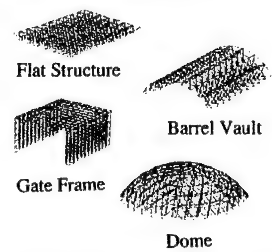


Fig.7 Design Type of CFRP Space Frame

OHP-4: General Technologies of The CFRP Space Frame

Development of Space Frame and Monocoque Panel with CFRP For Large-span Structures by ***Kenichi SUGIZAKI***

The CFRP Space Frame | Applied Buildings

Photo 1:
< The Refreshment Room of
Toray Industries Factory in Ehime >
Roof Area: 350 m^2
Total Construction Terms:
March 1997 ~ September 1997

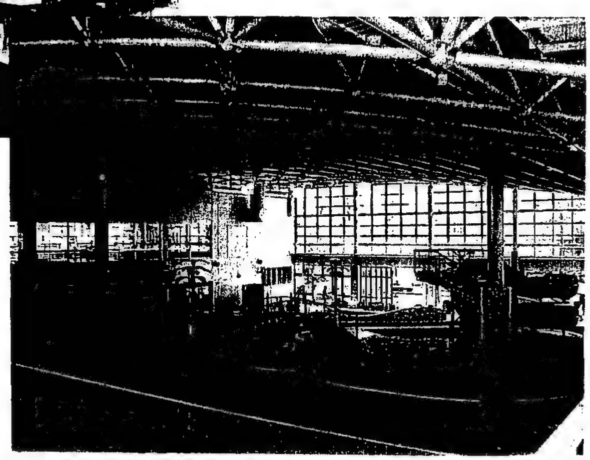


Photo 2:
< The City Pool of Mishima >
Roof Area: 1700 m^2
Roof Construction Terms:
July 1998 ~ August 1998
Finished: March 1999

OHP-5: The applied Buildings of The CFRP Space Frame

Development of Space Frame and Monocoque Panel with CFRP For Large-span Structures by ***Kenichi SUGIZAKI***

The CFRP Space Frame | Eagy Construction

CFRP Space Frame was used as a roof structure.

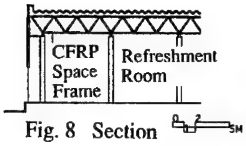
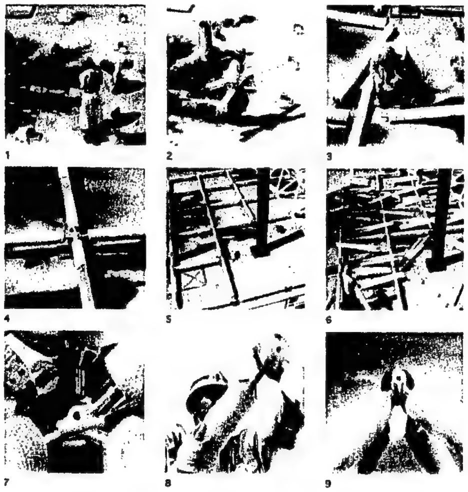
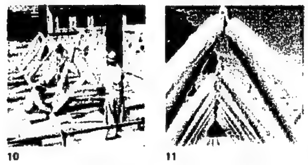


Fig. 8 Section

Phpto 3 External view



Phptos 4 Assembling work on the ground



Phpto 7 Easy lifting of a CFRP pipe member whose weight is only 7 kg

Photo 5 Finished the assembling work

CFRP Space Frame of about the total weight 8.5 tons which was assembled on the ground are installed by two of the fifty tons cranes on the steel frame columns of the height 6 meters.

Photo 6 Lift-up of the CFRP Space Frame Roof

The CFRP Space Frame | Construction -2

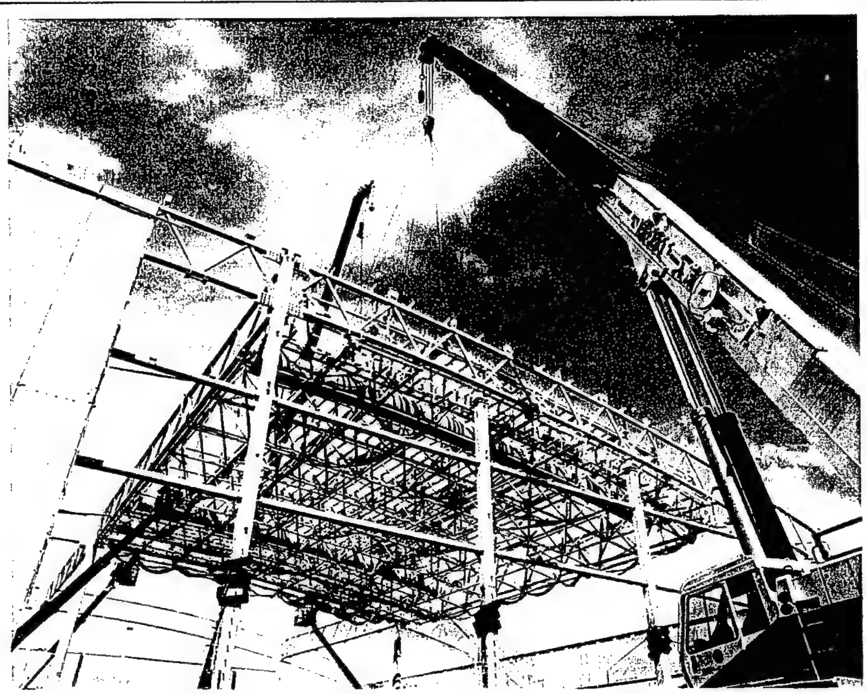


Photo 8 Lift-up the CFRP Space Frame of the Mishima city pool

The CFRP Space Frame | *Accumulation Cost*

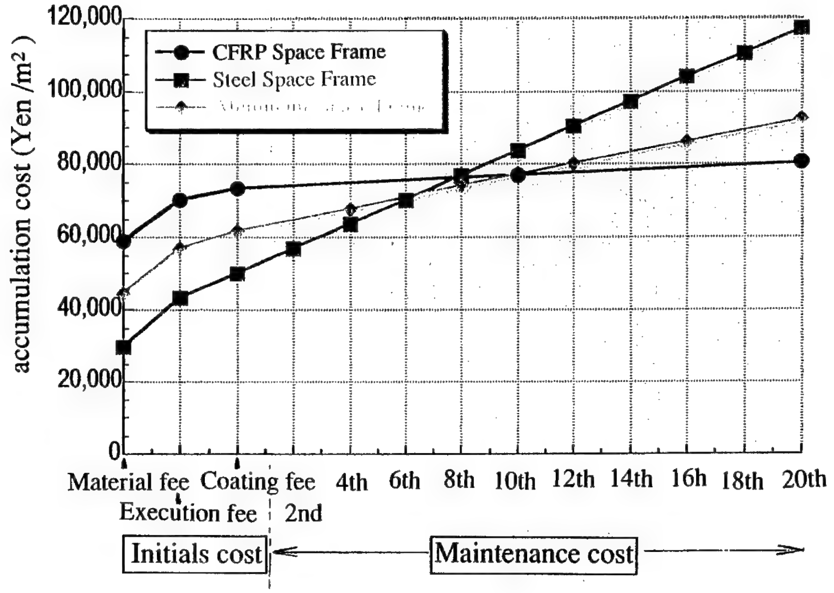


Fig. 9 The comparison of the accumulation cost of the Space Frames

OHP-8: Accumulation cost of The CFRP Space Frame

The CFRP Monocoque Panel | *General Technologies*

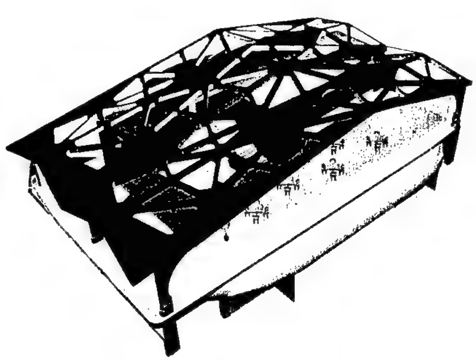


Fig. 10 Image Computer Grafic

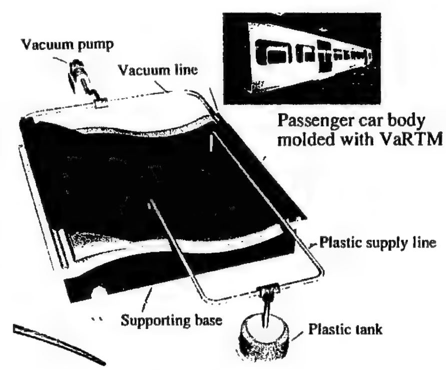


Fig. 12 Molding Method Example

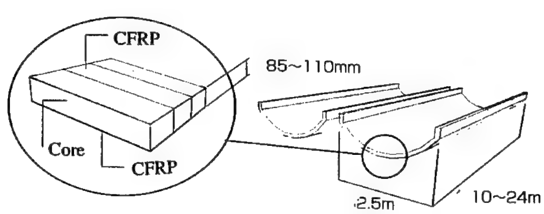


Fig. 11 Design Form Example

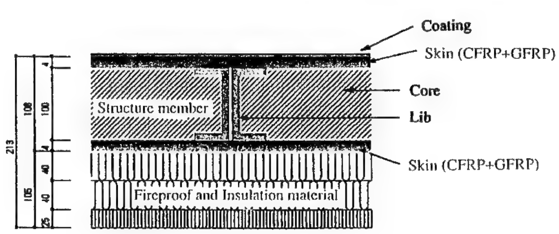


Fig. 13 Section Detail

OHP-9: General Technologies of The CFRP Monocoque Panel

The CFRP Monocoque Panel

Improving the Resistance to Earthquake by Replacing roofs

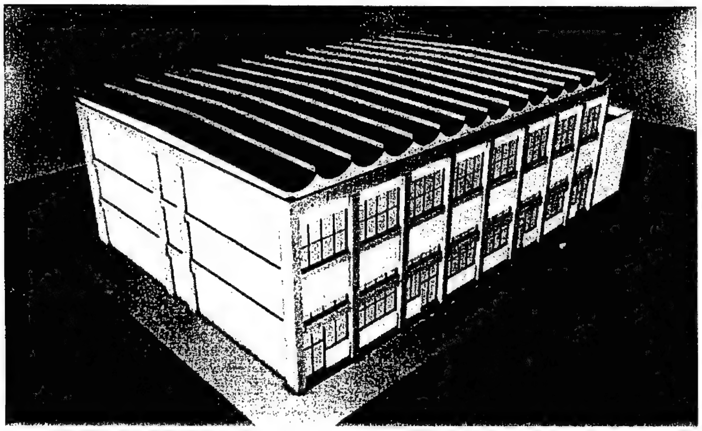
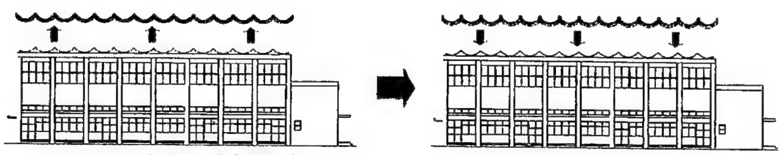


Fig. 14 Image CG of a elementary school gymnasium



a) removal of existent PCa panels

b) replace of CFRP new panels

Fig. 15 The replacing existent roof panels to CFRP new ones

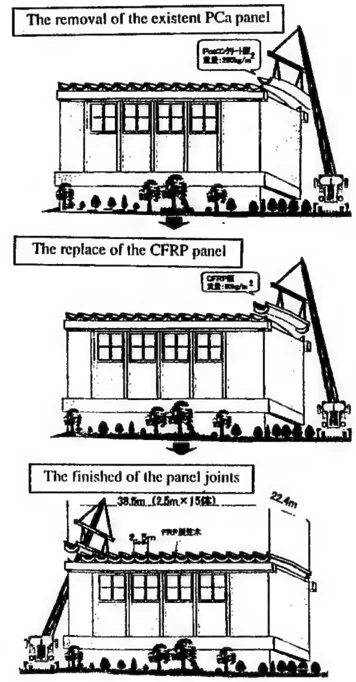


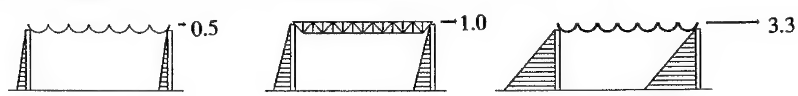
FIg.16 Construction Steps

The CFRP Monocoque Panel

Improving the Resitance to Earthquake and Eagy Construction

●Super-light weight

If CFRP monocoque panels are used, the super-light weight roof of about 40kg/m2 is realized .
The earthquake force from the roof added to the lower structure was compared with other systems of construction.



CFRP monocoque roof (about 40kg/m^2) — Steel girder roof (about 80kg/m^2) — PCa roof (about 250kg/m^2)

●Short term's excution

Because execution is easy, construction can be completed in the period such as a summer vacation.
It was compared with other systems of construction.

The plan of the CFRP monocoque panel

	6月			7月			8月			9月		
	10	20	30	10	20	30	10	20	30	10	20	30
							夏休み					
仮設工事												
Removal PCa												
Replace CFRP												
壁補強工事												
仕上工事												
諸検査												

The plan of the Steel girder

	6月	7月	8月	9月	10月
仮設工事					
PCa 版解体工事					
鉄骨屋根架設					
壁補強工事					
仕上工事					
諸検査					

The plan of the existence PCa panels

	6月	7月	8月	9月	10月
仮設工事					
PCa 版解体工事					
柱補強工事					
壁補強工事					
仕上工事					
諸検査					

The CFRP Monocoque Panel | Construction

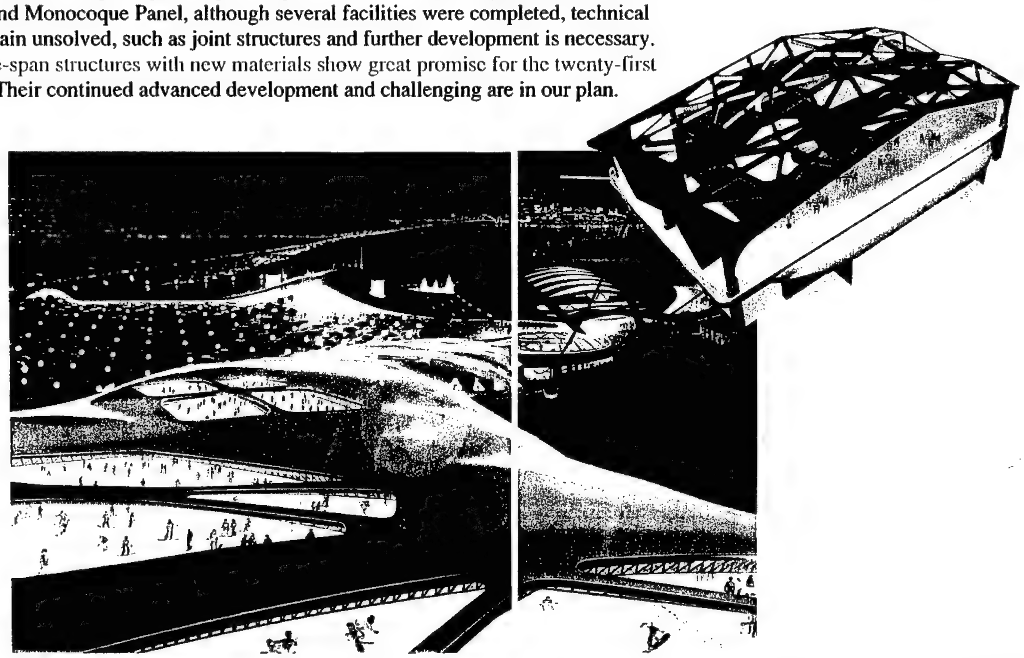
Photo 9 Lift-up a CFRP Monocoque Roof Panel of a elementary school gymnasium

The realization of the new created space using new materials | *Conclusion and Challenge*

< Conclusion and Challenge >

CFRP structural systems, we have been developing, have many excellent characteristics, such as well specific strength, light-weight, long-life, etc. With regard to both CFRP Space Frame and Monocoque Panel, although several facilities were completed, technical challenges remain unsolved, such as joint structures and further development is necessary.

These large-span structures with new materials show great promise for the twenty-first century. Their continued advanced development and challenging are in our plan.



The Application of Fiber Reinforced Plastics (FRP) in the Construction Field of Japan

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The Application of Fiber Reinforced Plastics (FRP) in the Construction Field of Japan

Kohzo KIMURA and Hiroya HAGIO
OBAYASHI Corporation Technical Research Institute

INTRODUCTION

Research and development of the concrete structures using the reinforcements consist of high-strength fibers have been underway since the early of 1980's in Japan. In 1986, the concrete curtain wall (Pre-cast concrete outer panel) mixed carbon fiber (chopped fiber) was installed, and a pre-stressed concrete bridge using carbon fiber reinforced plastic (CFRP) for the pre-stressed strand was constructed in Ishikawa prefecture in 1988.

In the civil engineering of Japan, the FRP reinforcements are mainly used for three objects. The first is on behalf of the conventional reinforcement bar and the strand. The second is the retrofit material for existing concrete structures. The demand of the carbon and the aramid fiber sheets for this use has been increased year by year since 1995, after the Hansin-Awaji earthquake. The last is on behalf of the steel members such as the steel pipe and the shape steel.

APPLICATIONS OF FRP REINFORCEMENT

The summary of some applications using FRP reinforcement for the structural materials and *"Carbon fiber Retrofitting System (CRS)"* we developed, are described.

(1) *Reinforcement and Tendon of Concrete member*

- Pretensioning bridge girder (1988)
- Pretensioning footing beam (1989)

(2) *Pre-cast Concrete panels*

The advanced fibers such as the carbon fiber and the aramid fiber have some superior merits, light weight and non-corrosion etc, compared with steel. The reinforced concrete panel using FRP reinforcement makes the cover concrete decrease and the concrete panel lighter than the conventional one using the reinforcing bar. Further the pre-stressed concrete panel using FRP tendon leads the panel strong against bending force and brings about the thin thickness.

- Electromagnetic wave shield Curtain wall using the FRP reinforcement (1993)
- Electromagnetically TV signal permeable curtain wall (1995)
- Thin Step board of the indoor stair (1995)
- Light-weight Roof panel (1998)

(3) *FRP pedestrian bridge* (1996)

(4) W*ooden beam reinforced CFRP laminates* (1997)

(5) *Retrofitting of the existing structure* (1988)

Since the Hansin-Awaji earthquake, seismic retrofit of columns with FRP

becomes popular. The top reason is easy application works without special craftsmanships. As it is possible not to get required performance when quite a nonprofessional are worked. The associate is organized to learn right works and the knowledge about FRP and evaluated the skill. This FRP technique is also successfully applied for beams. Since a beam always has a slab, the slab obstructs to form closed type transverse reinforcement only with carbon fiber sheets. So the authors developed a technique of fixing the carbon fiber sheets with plates and bolts to the both sides of the beam. Judging from the experiments, it is confirmed that the beam retrofitted with FRP is more ductile than unretrofitted the beam. These design methods of the retrofitted beams are researched. CRS-BM method of them is integrated at the design method and the works, and has the evaluation from the Japan Building Disaster Prevention Association. Additionally, retrofit of walls is tried applying the method of the anchorage of the retrofit of beam. The method is not more effective in comparison with the retrofit of beams. It is charming that the thickness of the wall do not increase, as if retrofitted, when the width of a corridor is regulated by lows. In Japan there are many buildings that the retrofit is necessitated. More and more the demand will increase.

(6) *Anchorage of FRP Pre-stressing Tendons*

In order to make good use of FRP tendons the anchorage system is needed. PC strands has useful anchorage system developed by many studies. Almost FRP tendons have the shortcoming that they don't resist against the shear force. Therefore the corners must be chamfered on the occasion of wrapping columns and beams with FRP. It is difficult to gripe with the same method. In a general way, the pipes infilled with swelling agent are used as the anchorage. But it takes one day at the least to give full strength. And the pipes must be thrown away per one usage. The method of dry-anchorage system as a wedge is desired. In particular when members pre-stressed with FRP tendons are produced, the wet-anchorage system is hardly used at the reason of the cost and labor time. So the dry-anchorage systems are introduced. And the behavior of FRP tendons with the dry-anchorages is reported.

IN CONCLUSION

The Applications of Fiber Reinforced Plastics are described in the construction field of Japan. These new materials just begin and have many possibilities. For the future it is important to gather in data for years.

The Application of Fiber Reinforced Plastics (FRP) in the Construction Field of Japan

Kohzo KIMURA

Hiroya HAGIO

OBAYASHI Corporation

Technical Research Institute

The practical applications of FRP reinforcement in construction

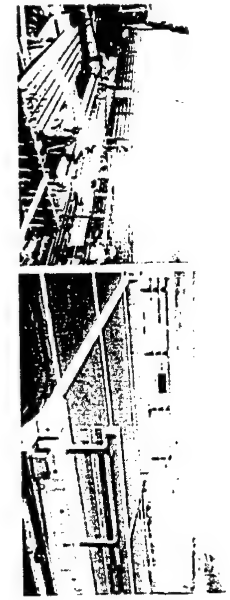
(Year)

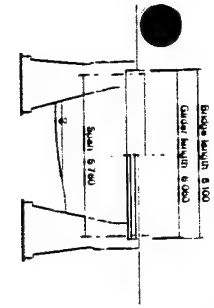
Classification	1985–2000
Main structural member	▼ Pretensioning Footing beam; ▼ Pretensioning Step board of indoor stair; ▼ Prestressed Wooden beam; Roof truss structure ▼; ▼ Pretensioning Roof panel
Secondary(Sub) Sturactural member	▼ Concrete Curtain wall mixed Chopped Fiber; ▼ Electromagnetic wave shield wall; ▼ OA Floor panel; ▼ Parapet & Louver; ▼ Partition wall; ▼ Electromagnetically TV signal permeable curtain wall
Foundation	▼ Reinforcement of shotcrete on slop; ▼ Degaussing pile; ▼ Ground anchor; ▼ Foundation of high voltage facility; ▼ Concrete reinforcement of shield wall
Repair & Retrofit	▼ Repair of chimney; ▼ Retrofit of historical wooden beam; ▼ Retrofit of highway bridge pier
civil engineering structure	▼ Hexagonal marine structure; ▼ Cable-stayed bridge; ▼ FRP pedestrian bridge; ▼ Pretensioning bridge girder; Floating jetty ▼; ▼ Linear beam girder; ▼ Sea shore structure
Temporay Construction	▼ Reinforcement of form with finish; ▼ Temporary tendon; ▼ Pilot rope; ▼ Stay cable for catwalk

Shinmiya Bridge

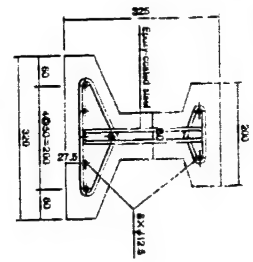
Name	Shinmiya Bridge
Location	Ishikawa Prefecture
Application	Tendon
FRP type	CFCC 1x7 12.5mm
Type of structure	Pretensioned simple slab bridge (Length) 6.1m, (Width) 7.0m
Completed	1998

* CFCC: Carbon Fiber Composite Cable





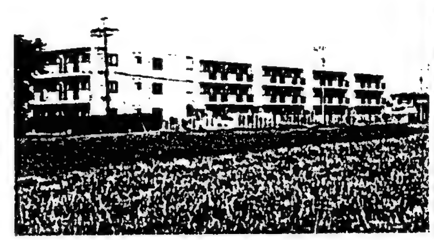
Elevation of Bridge



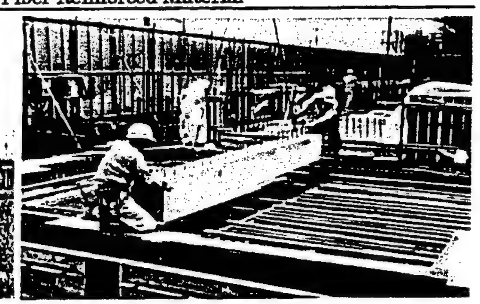
Section of PS Girder

MC Heights Kashiwa

Name	MC Heights Kashiwa
Location	Kashiwa City, Chiba Prefecture
Application	tendon, main reinforcement and shear reinforcement of Pretensioning prestressed reinforced footing beams
FRP type	Tendon; RA13, Main reinforcement; RA11S, Shear reinforcement; RA7
Completed	1992
Remarks	The first application of a CFRM in a major structural member of a building, following authorization by the Ministry of Construction. Aramid Fiber rods used in upper footing beams binders of 3-story reinforced concrete apartment block. CFRM: Continuous Fiber Reinforced Material



View of MC Heights Kashiwa



Installation of PC beam

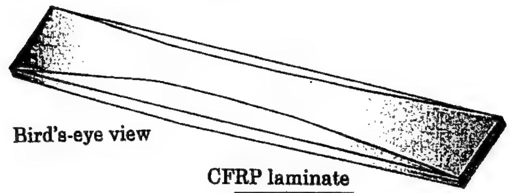
Electromagneticall TV signal permeable Curtain Wall

Name	Denki Building
Location	Heiwa-odori Avenue in Hiroshima, Hiroshima Prefecture
Application	Reinforcement of Curtain Wall
FRP type	3mm and 7mm Aramid FRP rod (total 21,400m)
Completed	1995

View of Denki Building

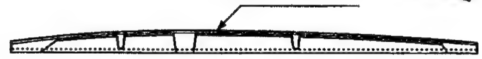
Shinagawa Inter-City —Skyway—

Name	Shinagawa Inter City
Location	Minato-ku, Tokyo metropolitan area
Application	Reinforcement of Roof panel (total 156 pieces)
FRP type	CFRP laminate: 4.5mm X 50mm and 25mm (total length of CFRP: about 5,000m)
Completed	1998

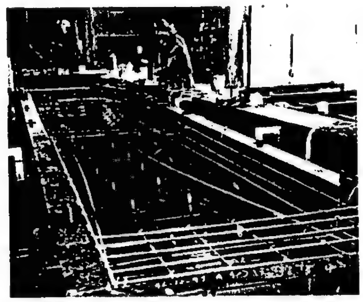


Bird's-eye view

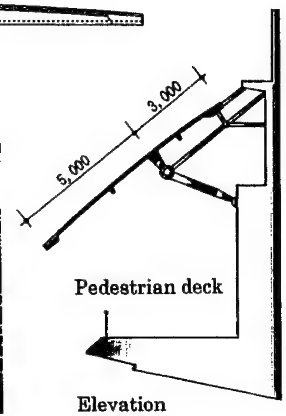
CFRP laminate



Section



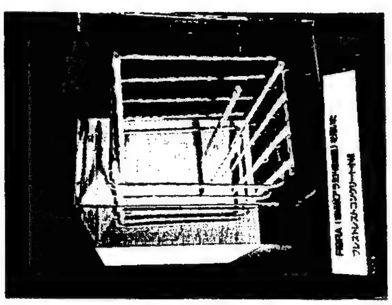
Arrangement of reinforcements and tendons



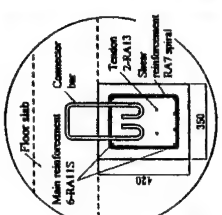
Pedestrian deck

Elevation

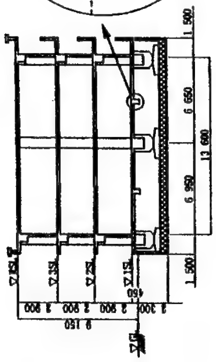
MC Heights Kashiwa



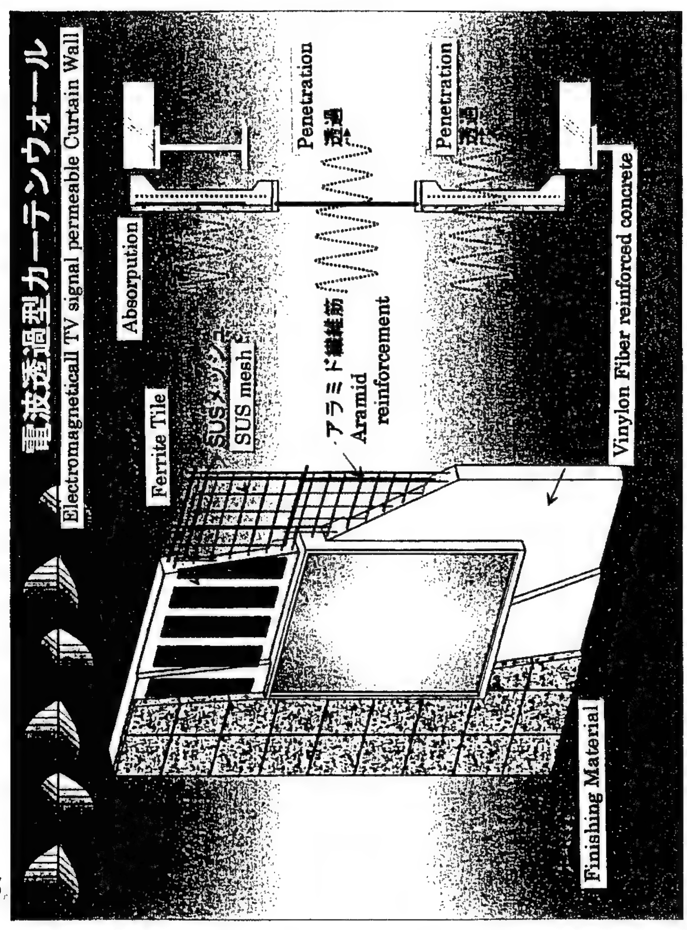
Arrangement of FRP reinforcement



Detail of Beam section

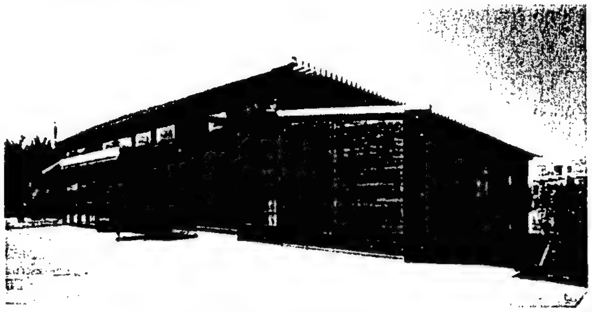


Elevation

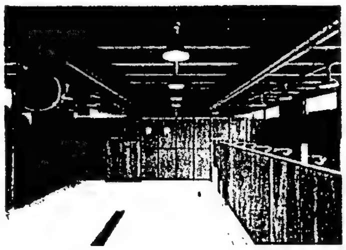


Post-tensioning Prestressed Wooden beam

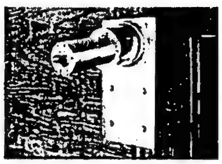
Name	Material Laboratory Center
Location	Kiyose City, Tokyo metropolitan area
Application	Post-tensioning tendon
FRP type	CFRP laminate: 4.5mm X 50mm
Completed	June 1997



Outside View of Wooden Structure

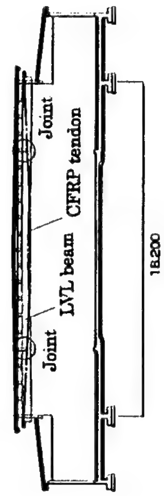


Prestressed Wooden beam (inside of the building)

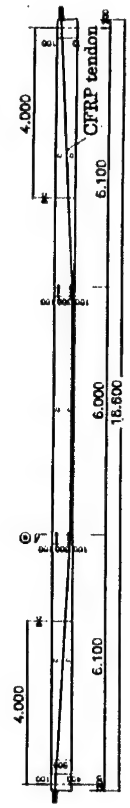


Anchorage of CFRP tendon

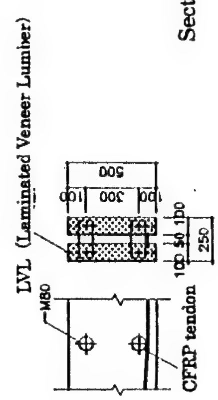
Post-tensioning Prestressed Wooden beam



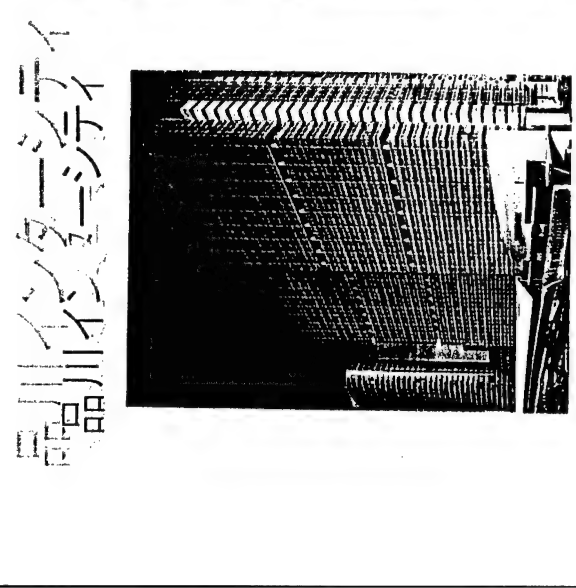
Elevation



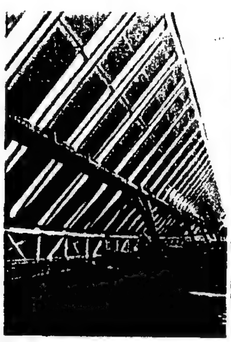
Detail of Prestressed Wooden beam



Section of beam



Shinagawa Inter-City



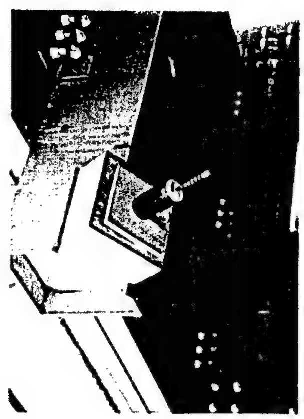
View from pedestrian deck

Roof panel of Skyway

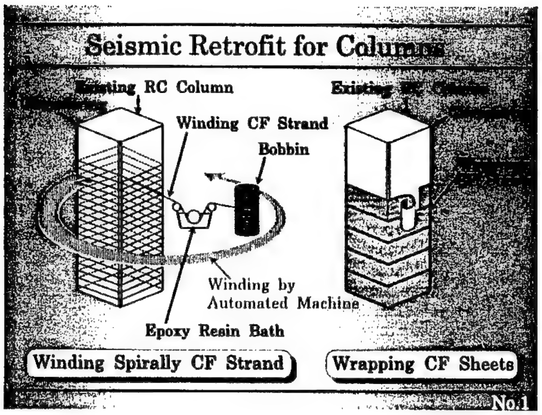
FRP Continuous Cable-Stayed Bridge

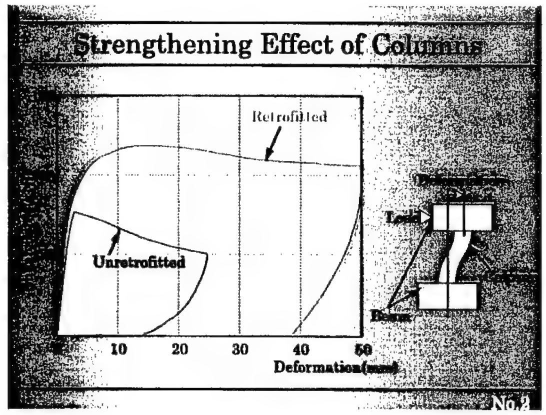
Name	FRP pedestrian bridge
Location	Tsukuba City, Ibaragi Prefecture
Type of structure	Three-span continuous cable-stayed bridge (all FRP) 20m long with a center span 11m, 2m wide deck
FRP type	Cable: CFRP 8mm, CFCC 12.5mm, Pultruded GFRP member
Completed	March 1996
Remarks	The joints were bolted using fiber reinforced polymer (FRP) bolts. The total weight of the bridge, including the handrail and the staircase, is 4.4 tons.

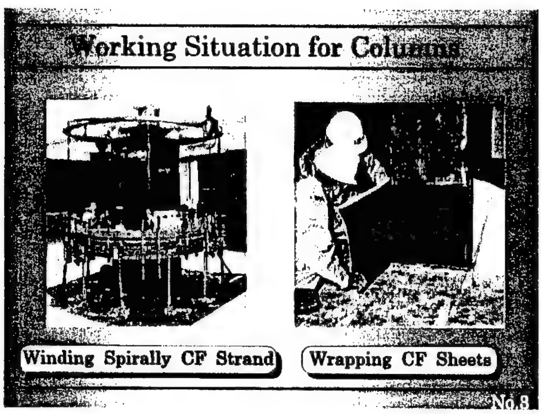
Outside of FRP bridge

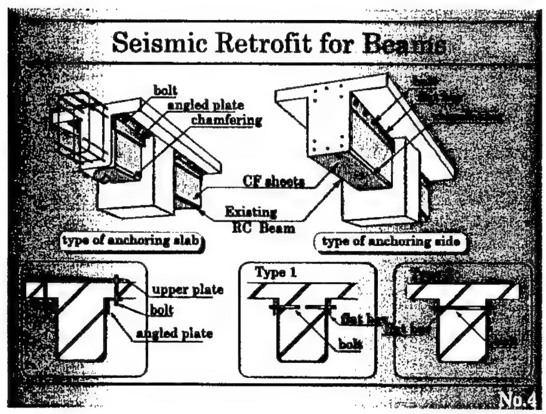


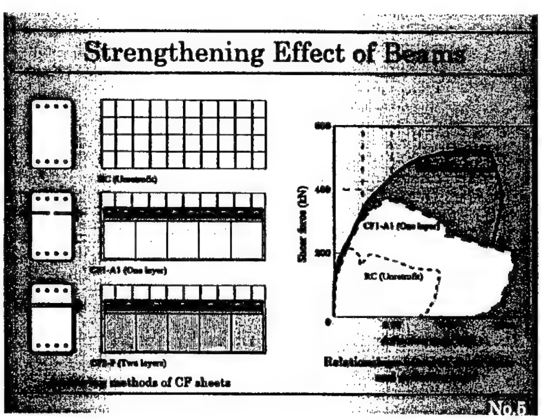
Details of joints and anchorage of CFRP tendon

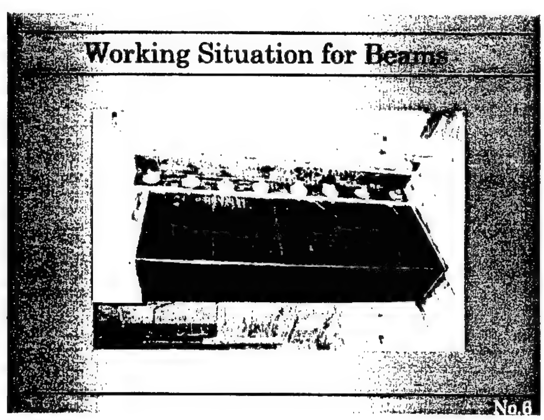

Seismic Retrofit for Columns
RC Column
Winding CF Strand
Bobbin
Winding by
Automated Machine
Epoxy Resin Bath
Winding Spirally CF Strand
Wrapping CF Sheets
No.1

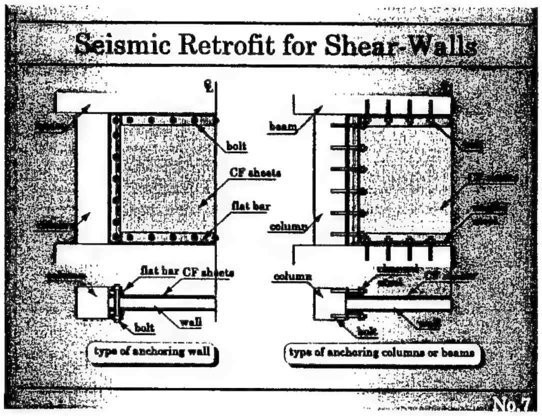

Strengthening Effect of Columns
Retrofitted
Unretrofitted
10
20
30
40
50
Deformation(mm)
Beam
No.2

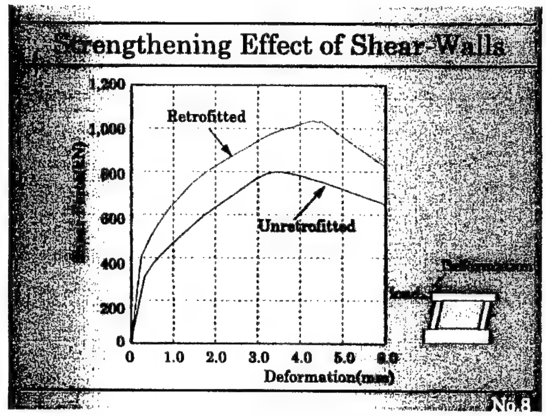

Working Situation for Columns
Winding Spirally CF Strand
Wrapping CF Sheets
No.3

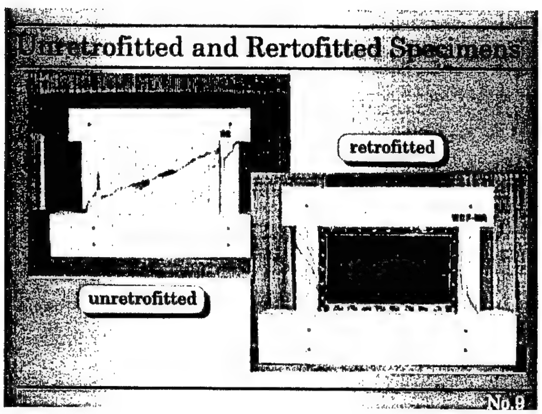

Seismic Retrofit for Beams
bolt
angled plate
chamfering
CF sheets
Existing
RC Beam
type of anchoring slab
type of anchoring side
upper plate
bolt
angled plate
Type 1
flat bar
bolt
No.4

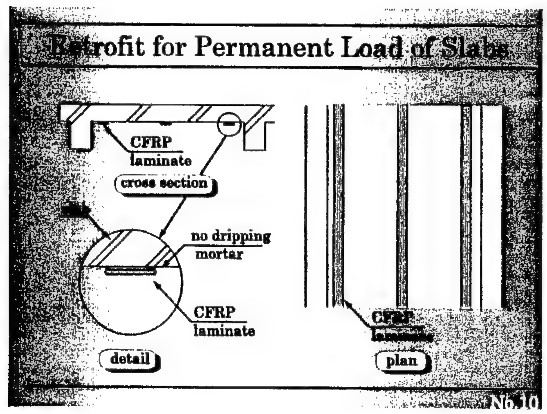

Strengthening Effect of Beams
CF1-A1 (One layer)
RC (Unretrofit)
methods of CF sheets
No.5

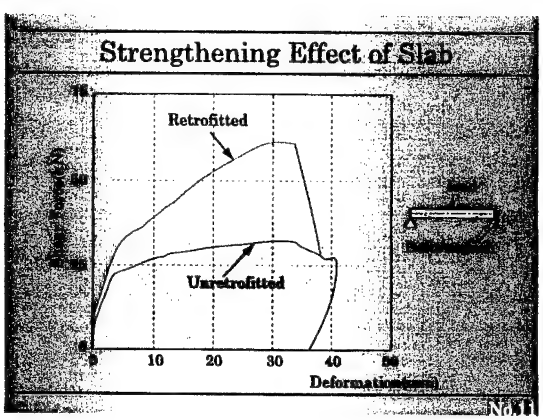

Working Situation for Beams
No.6

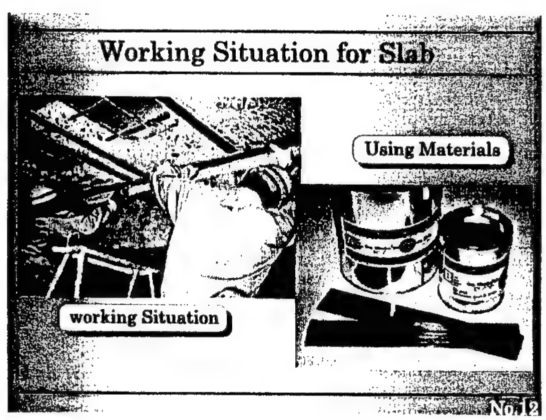

Seismic Retrofit for Shear-Walls
bolt
CF sheets
flat bar
beam
column
flat bar CF sheets
wall
type of anchoring wall
type of anchoring columns or beams
No.7

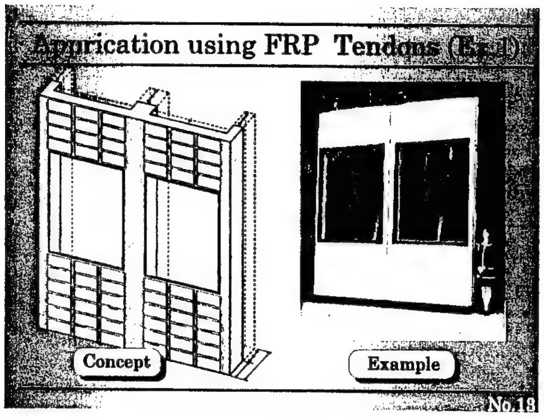

Strengthening Effect of Shear-Walls
Retrofitted
Unretrofitted
Deformation(mm)
No.8

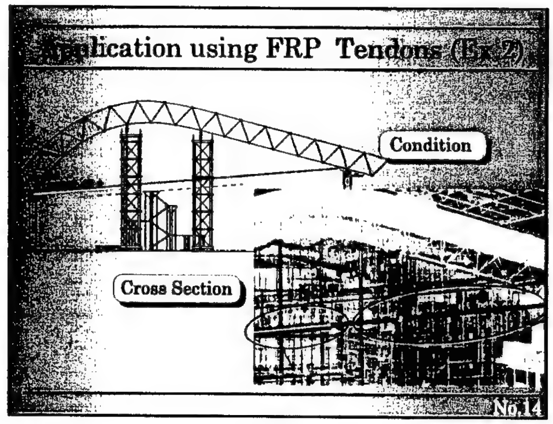

Unretrofitted and Rertofitted Specimens
retrofitted
unretrofitted
No.9

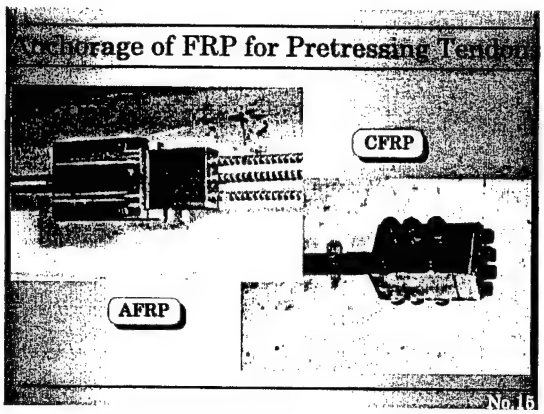

Retrofit for Permanent Load of Slabs
CFRP laminate
cross section
no dripping mortar
CFRP laminate
detail
plan
No.10

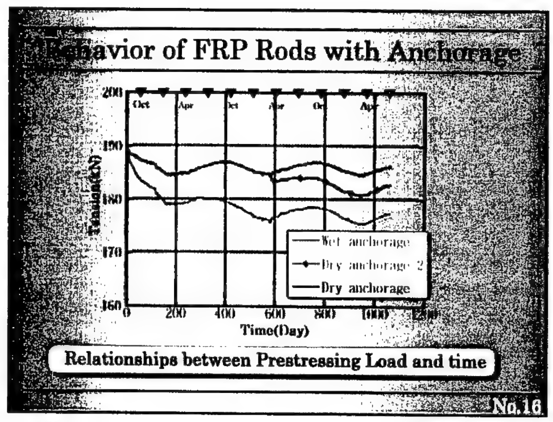

Strengthening Effect of Slab
Retrofitted
Unretrofitted
Deformation(mm)
No.11


Working Situation for Slab
Using Materials
working Situation
No.12


Apprication using FRP Tendons (Ex.1)
Concept
Example
No.13


Application using FRP Tendons (Ex.2)
Condition
Cross Section
No.14


Anchorage of FRP for Pretressing Tendons
CFRP
AFRP
No.15


Behavior of FRP Rods with Anchorage
Wet anchorage
Dry anchorage 2
Dry anchorage
Time(Day)
Relationships between Prestressing Load and time
No.16

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建物一五〇－S四
電話(〇四二)七六九－五二〇八
ファックス(〇四二)七六九－五二三六

CDW 2001

August 23(Thu) and 24(Fri), 2001

Albuquerque, New Mexico, USA

Organizer: Steven Huybrechts
Stephen W. Tsai
Yasushi Miyano

Advantage:

- Before the AIAA Conference on August 27 to 30, 2001
- Lab Tours of Air Force Research Laboratory and Sandia National Laboratory

CDW 2000

The Third Composites Durability Workshop
August 22–23, 2000, Tokyo, Japan

Workshop Secretariat

Masayuki Nakada (Director, Kanazawa Inst. of Tech.)
Nobumasa Iwashita (Kanazawa Inst. of Tech.)
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